Strategic optimization of offshore wind farm installation

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April 19, 2017

ABSTRACT

This work describes logistical planning of offshore wind farm installation through mathematical optimization.

Two optimization models are developed to analyse cost-effective port and vessel strategies for offshore installation operations. By applying principals of mixed integer linear programming (MILP), the two models seek to minimize total costs through port- and vessel related decisions. The models cover offshore transportation and installation of a given amount of wind turbines. Different vessel strategies, ports, time horizon and weather restrictions are considered in the models.

Several deterministic test cases with fixed cost parameters and historic weather data are implemented in AMPL and run with the CPLEX solver. The test cases show promising results in aiding strategic decisions, and the models provide valuable insight into economic impact of such decisions. The results indicate that decision aid could be more reliable if smaller subproblems are considered, potentially in a stochastic framework.

ACKNOWLEDGEMENT

I would like to express my gratitude to my thesis supervisor Dag Haugland at the Department of Informatics at the University of Bergen. Our frequent meetings have ensured the progress of this work, and I highly appreciate his thorough feedback along the way.

I would also like to thank my contacts from SINTEF Ocean and the LEANWIND project: Elin Espeland Halvorsen-Weare and Lars Magne Nonås. Their help in formulating the project and quickly answering questions throughout this work has been very valuable.

CONTENTS

1 INTRODUCTION 10
2 OFFSHORE WIND 11
 2.1 Offshore wind status 11
  2.1.1 Installed capacity 11
  2.1.2 Levelized cost of energy (LCOE) 11
  2.1.3 Potential cost reductions 12
 2.2 Installation process 12
  2.2.1 Port strategy 13
  2.2.2 Vessel availability 13
  2.2.3 Vessel strategy 13
  2.2.4 Turbine components 14
  2.2.5 Weather restrictions 15
  2.2.6 Estimating weather windows 16
 2.3 Previous work 17
  2.3.1 Mixed integer linear programming (MILP) 17
  2.3.2 SINTEF Ocean's model 18
  2.3.3 Alternative modeling 19
 2.4 Summary 20
3 MODEL FORMULATION: MODEL 1 21
 3.1 Set definitions 22
  3.1.1 Vessels 22
  3.1.2 Components and turbine locations 22
  3.1.3 Ports 23
  3.1.4 Cycles 23
 3.2 Assigning operations 23
  3.2.1 Picking vessels and ports 23
  3.2.2 Routing 24
  3.2.3 Transportation and installation 24
  3.2.4 Positioning 24
  3.2.5 Routing constraints 25
  3.2.6 Operational constraints 26
  3.2.7 Loading restrictions 27
 3.3 Time tracking 27
  3.3.1 Continuous time 27
  3.3.2 Cycle time 28
 3.4 Weather windows 30
  3.4.1 Weather window parameters 31
  3.4.2 Weather window restrictions 32
 3.5 Objective function 34
 3.6 Summary 35
4 MODEL SIMPLIFICATION: MODEL 2 36

4.1 Simplifications 36
4.1.1 Omitting routing 36
4.1.2 Limiting choices of installation 36
4.2 Redefining sets 36
4.2.1 Vessel strategies 36
4.2.2 Vessel strategy duplication 37
4.2.3 Cycles and ports 37
4.2.4 Turbines 37
4.3 Redefining decision variables and constraints 38
4.3.1 Redefining decision variables 38
4.3.2 Redefining assignment 39
4.3.3 Special ordered sets of type 2 (SOS2) 39
4.4 Redefining time restrictions 40
4.4.1 Redefining time variables and parameters 40
4.4.2 Redefining cycle time 41
4.5 Redefining weather windows 43
4.5.1 Redefining weather window parameters 43
4.5.2 Redefining weather window restrictions 44
4.6 Redefining the objective function 46
4.7 Summary 47
5 EXPERIMENTS 48
5.1 Gathering data 48
5.1.1 Fixed port cost 48
5.1.2 Distances 49
5.1.3 Vessel efficiency 49
5.1.4 Loading and assembly strategy 49
5.1.5 Vessel costs 50
5.1.6 Time horizon and weather window input 50
5.2 Defining ports and vessel strategies 51
5.2.1 Wind farm and ports 51
5.2.2 Vessel strategy: Feed 51
5.2.3 Vessel strategy: Bunny transit 52
5.2.4 Vessel strategy: Unmounted transit 52
5.2.5 Port transit time 53
5.3 Numerical experiments and results 53
5.3.1 Experiment 1: 20 turbines and 1 month 53
5.3.2 Experiment 2: 40 turbines and 3 months 55
5.3.3 Experiment 3: 100 turbines and 5 months 57
5.4 Discussion 58
5.4.1 Computational capability 58
5.4.2 Model credibility 58
5.4.3 Interpretation of vessel strategy decisions 59
5.4.4 Interpretation of port decisions 59
6 CONCLUSIONS 61
6.1 Comparison of models 61
6.2 Deterministic analysis 62

6.3 Dealing with uncertainty 62
6.4 Strategic decisions for large offshore wind farms 62
6.5 Future work 63
Appendices 64
A MATHEMATICAL FORMULATION OF MODEL 1 65
A.1 Sets 65
A.2 Parameters 65
A.3 Variables 66
A.4 Objective function 66
A.5 Constraints 67
A.6 Weather window parameters 68
A.7 Weather window variables 69
A.8 Weather window constraints 69
A.8.1 Transit 69
A.8.2 Jack-up 70
A.8.3 Installation 70
A.8.4 Jack-down 70
B MATHEMATICAL FORMULATION OF MODEL 2 71
B.1 Sets 71
B.2 Parameters 71
B.3 Variables 72
B.4 Objective function 72
B.5 Constraints 73
B.6 Weather window parameters 74
B.7 Weather window variables 74
B.8 Weather window constraints 75
B.8.1 Transit 75
B.8.2 Jack-up 76
B.8.3 Installation 76
B.8.4 Jack-down 76

LIST OF FIGURES

Figure 2.2.1	Fred. Olsen's Bold Tern - a self-propelled jack-up vessel.	14
Figure 2.2.2	An illustration of top-structures by author	15
Figure 5.3.1	Gantt chart presenting optimal installation schedule (Solution 1.1) for Experiment 1.	54
Figure 5.3.2	Gantt chart presenting the best installation schedule (Solution 2.1) for Experiment 2.	56

LIST OF TABLES

Table 5.1.1	Weather restriction ranges for vessel operations	51
Table 5.2.1	Port data input	51
Table 5.2.2	Data for the considered strategies	52
Table 5.2.3	Transit time in between different ports and wind farm with different strategies	53
Table 5.3.1	Optimal strategies for 20 turbines with 1 month time horizon.	54
Table 5.3.2	Best solution obtained for 40 turbines with 3 months time horizon after 10,000 seconds computer time.	56
Table 5.3.3	Best solution obtained for 100 turbines with 5 months time horizon after 20,000 seconds computer time.	58

ACRONYMS

CAPEX Capital Expenditure

EWEA European Wind Energy Association

DECOFF Decision Support for Installation of Offshore Wind Turbines

EY Ernst & Young

GWEC Global Wind Energy Council

IRENA International Renewable Energy Agency

LCOE Levelized Cost of Energy

LEANWIND Logistic Efficiencies And Naval architecture for Wind Installations with Novel Developments

MARINTEK The Norwegian Marine Technology Research Institute

MILP Mixed Integer Linear Programming

NORCOWE The Norwegian Centre for Offshore Wind Energy

NREL National Renewable Energy Laboratory

RAB Renewables Advisory Board

ROV Remotely Operated Vehicle

SOS2 Special Ordered Sets of Type 2

VRP Vehicle Routing Problem

1

INTRODUCTION

Renewable energy is a growing industry within the energy sector. The growth is motivated by issues like the challenge of global climate change, the increasing need for energy, and new market opportunities. Harvesting energy from the wind is today becoming a developed renewable energy technology. Operating offshore involves greater challenges than onshore.

There are several advantages of utilizing offshore wind over its onshore counterpart. First of all, the wind resources are greater at sea than on land. This makes the offshore locations offer more potential energy through higher capacity factors with more steady production. Another common argument is that there is less competition for offshore areas, so that potential land use conflicts are avoided (Breton and Moe, 2009). Offshore logistics also offer better potential to transport the continuously increasing size of wind turbine components (Snyder and Kaiser, 2009). As the different components of a wind turbine grow in size, transportation of these is more likely to be feasible at sea than on land.

However, these benefits may all lose their relevance due to the higher provisional costs related to offshore wind farms. This causes the price of electricity, generated at offshore wind farms, to exceed other energy sources even though the potential is great. With offshore wind still being a young technology, today's many challenges contributing to high costs are expected to be reduced in the near future. Some propose a reduction of costs by up to 30 % by 2030 (IRENA, 2012).

Constructing an offshore wind farm requires a lot of logistical planning. Vessels and/or barges must transport and install components in a demanding environment. The challenges include restricting weather conditions contributing to delays on very costly operations.

This work seeks to contribute to cost reduction by developing tools to optimize the logistics of installing offshore wind turbine components. Chapter 2 presents the current status of offshore wind farms and the process of constructing such farms. Chapter 3 introduce a detailed optimization model with the purpose of minimizing total logistical costs of installation. In Chapter 4, the model formulated in Chapter 3 is simplified in order to tackle problems of larger size. Chapter 5 presents realistic numerical experiments run with the simplified model. Finally, Chapter 6 concludes how the models can be used and suggests possible future work that can be done to potentially strengthen decision support on offshore wind farm installation.

2

OFFSHORE WIND

2.1 OFFSHORE WIND STATUS

2.1.1 *Installed capacity*

Offshore wind energy is a rapidly growing industry. A total of 754 (EWEA, 2016) new offshore turbines were connected to grid in Europe in 2015, with an installed power of 2,019 MW (EWEA, 2016). The cumulative installed power from offshore wind in Europe in 2016 was 12,631 MW (WindEurope, 2017). This capacity was supported by a total of 3,589 (WindEurope, 2017) grid-connected wind turbines in 10 European countries in January 2017. The turbines installed in 2016 reached an average size of 4.8 MW (WindEurope, 2017). Europe has more than 91 % (GWEC, 2015) of the world's grid-connected offshore wind turbines.

The European offshore wind industry mentions 26.4 GW (EWEA, 2016) of installed offshore wind power that is consented to be constructed over the next decade.

Offshore wind farms in the planning phase are particularly interesting for the current thesis work due to the high relevance of an optimization tool at a planning stage. A total of 65.6 GW (WindEurope, 2017), more than five times the cumulative installed capacity from offshore wind in 2016, are currently estimated to be in the planning phase.

2.1.2 *Levelized cost of energy (LCOE)*

To compare the cost of energy produced by different energy sources, a *levelized cost of energy (LCOE)* is often estimated:

$$\text{LCOE} = \frac{\text{Total costs related to the energy source}}{\text{Total amount of electrical energy produced from the source}}$$

This is the estimated net present total cost per energy unit for one specific energy source.

The calculation takes into account total investments and operational- and decommissioning costs with discount rates, and compares it to the total amount of expected energy production with discount rates. The idea is to get an estimate of which price one would have to pay per energy unit for the project to break even over its lifetime.

During 2016, a lot of achievements were made on the levelized cost of energy for offshore wind. A record low bid of € 60/MWh (Gosden, 2016) was put on a 350 MW project by Vattenfall. An estimate made by Bloomberg New Energy Finance (Mills, 2016) showed an average levelized cost of energy for offshore wind to be $ 126/MWh in H2 2016, a 28 % reduction in one year. This means the LCOE for offshore wind is rapidly approaching fossil fuel alternatives like coal- and gas power plants, where the LCOE range in between $ 50-100/MWh (Mills, 2016).

Major companies in the offshore wind industry agree that cost reduction of offshore wind is necessary and desirable. In a letter (Industry, 2016) to the governments of Europe prior to the Energy Council meeting in June 2016, industry parties urged public support and cooperation in order to achieve a levelized cost of energy of € 80/MWh by 2025.

2.1.3 *Potential cost reductions*

There are two main ways of reducing the LCOE of an energy source:

1. Reduce total costs of the energy source
2. Increase total energy production

The current work focuses on alternative 1, more specifically on reducing capital expenditure (CAPEX). A report by the Renewables Advisory Board (RAB) claims that installation and commissioning of an offshore wind farm make up about 26 % (RAB, 2010) of the CAPEX. These costs are dominated by costs related to installation vessels.

A report by the European Wind Energy Technology Platform (EWEA, 2014) mentions specifically the development of new logistic planning tools as a research priority for the offshore wind industry, and a report by Ernst & Young (EY) suggests supply chain optimization measures could lead to up to 3 % (EY, 2015) savings.

Both farm sites and turbines are expected to keep growing in size, and wind farm locations are expected to be placed further away from shore in deeper waters. These factors make the logistics of installation more complicated. Crucial aspects in planning the installation process include choosing the most cost-effective vessels available, figuring out how these vessels should be organized, and choosing which port(s) they should operate from.

2.2 INSTALLATION PROCESS

The process of installing an offshore wind farm is logistically challenging, implying high costs. There are many stages of logistical planning.

The current work considers the offshore stage, where all components are assumed available at potential ports. These components must be loaded and transported by specialized vessels to different turbine locations. The transported components must then be installed at turbine locations in a certain order.

The main stages of the process are therefore loading components at ports, transportation to turbine location and installation of components.

2.2.1 *Port strategy*

Turbine components must be transported from ports to turbine locations. Such ports can either be *manufacturing* ports or *assembly* ports (BVG, 2009).

Manufacturing ports are ports where components can be produced. These ports are usually far away from planned wind farms, and the use of high speed installation vessels is crucial if manufacturing ports are to be used.

Assembly ports are intermediate ports between manufacturing ports and the wind farm site. If an assembly port is used, manufactured turbine components must be transported here before they can be transported to the wind farm. Assembly ports are usually located closer to the wind farm, such that less transit is required by the specialized installation vessels.

The use of manufacturing ports can negate the need for any intermediate assembly port. Thus, manufacturing ports have potentially lower fixed costs and higher vessel requirements than assembly ports.

2.2.2 *Vessel availability*

A big challenge in relation to CAPEX is the high charter rates of vessels. The main vessels used are jack-up vessels. These vessels lower pillars into the seabed and create stable platforms where lifting operations can be performed offshore. Jack-up vessels can be self-propelled or require tugs to be mobilized.

Other non-jack-up vessels and barges (with tugs) may support component transport. Chartering of vessels is expensive with limited availability.

The main installation season for offshore wind farms is during summer when weather is less harsh. Because of a growing market, more vessels are being developed specifically for offshore wind installation, e.g. Fred. Olsen's Bold Tern (see Figure 2.2.1). Increased vessel availability, as well as more vessel options, make optimization analysis for installation fleet more relevant.

2.2.3 *Vessel strategy*

According to a report by BVG Associates (BVG, 2009), there are two main vessel strategies on how to construct an offshore wind farm.

The first strategy can be referred to as *feeding*. Feeder vessels and barges transport components to the wind farm where installation vessels are positioned to receive components and start installation. The installation vessels stay in the farm as the feeder vessels and barges return to a port to reload components. High utilization of installation vessels can be obtained

Figure 2.2.1.: Fred. Olsen's Bold Tern - a self-propelled jack-up vessel.

Credit: Fred. Olsen Windcarrier. Accessed: 19-04-2017:
`http://windcarrier.com/blog/case-studies/borkum-riffgat/`

with this strategy. However, transfer of components from feeder vessels to installation vessels offshore is more challenging and time demanding than port loading.

The second strategy can be referred to as *transiting*. Multi-purpose vessels perform both transportation and installation of turbine components. Less vessels are required in this strategy, but it may be inefficient with respect to time and vessel utilization.

2.2.4 *Turbine components*

On a farm with identical turbines, all wind turbines consist of the same set of component types. The component types can be split into three main categories: Sub-structures, top-structures and cable.

Sub-structures include components like foundation and transition piece. Foundations of an offshore wind turbine can vary. The most common foundation is the *monopile* support structure installed at about 80 % (EWEA, 2016) of all offshore wind farms. This is a cylindrical steel tube that is drilled into the seabed by a jack-up vessel.

Compared to alternatives, monopiles are considered easy to install in shallow waters. Other types of foundations include jacket and tripod concepts. These concepts are more relevant for deeper waters.

The transition piece connects the subsea foundation to the top-structures. The foundation and the transition piece may be installed simultaneously or in separate operations.

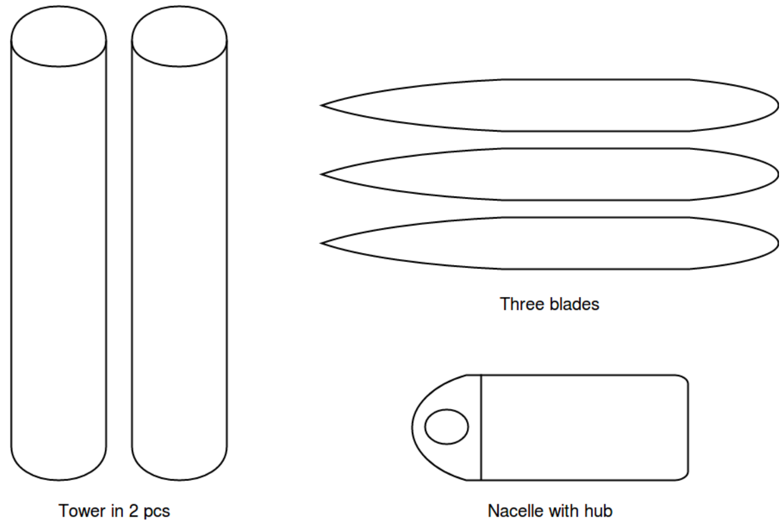

Figure 2.2.2.: An illustration of top-structures by author

Top-structures can only be installed after all sub-structures are in place. These structures consist mainly of tower, nacelle, hub and three blades (see figure 2.2.2). The top-structure components can be partly assembled onshore in different setups, e.g. tower, nacelle and hub together and three separate blades. The top-structures may also be assembled entirely onshore as one complete piece.

Cables are installed using cable installation vessels with the assistance of Remotely Operated Vehicles (ROVs) and/or divers.

In addition to all these components, sub-stations must also be installed using heavy-lift vessels. Most sub-stations convert AC energy from the wind turbines to DC energy. This is done to achieve the least loss of energy upon connecting the electricity to an onshore grid. Smaller sub-stations with AC transfer can be used for wind farms close to the shore. All turbines are linked to such stations through cables.

A technical report by the National Renewable Energy Laboratory (NREL, 2013) suggests some of the greatest opportunities for logistical optimization are related to installation of top-structures. The options are few on how to perform installation of sub-structures, cables and sub-stations, thus these installations are less interesting in an optimization context.

2.2.5 *Weather restrictions*

One of the biggest challenges in the installation process is the weather conditions. The main restrictions occur due to wind and waves. Precise operations, such as installation of blades, may become impossible for the vessels under certain wind or wave conditions.

It has been estimated that the availability of a turbine for maintenance is only about 50-75 % of the time (Breton and Moe, 2009). Placing turbines in more sheltered waters is naturally undesirable, so when considering the high potential of energy harvest on locations with consistent winds, this challenge is crucial to deal with. Due to expenses related to the installation process, it is important that the supply chain and inventory system leading up to the installation is optimized such that good weather conditions are exploited.

Installation of components require lifting operations which are mainly restricted by wind conditions, whereas positioning of an installation vessel (i.e. jacking up) is mainly dependent on wave conditions.

Research done by Barlow et al. (2015) demonstrate through a simulation model that weather window utilization has high impact on logistical operation durations. Vessel development focusing on improving vessel capacity for carrying components is suggested through simulation to have little impact on operation duration reductions. In contrast, a small improvement in operational weather limitations, or prolonged weather windows, may contribute largely to reduced delays.

By changing strategy when installing blades to achieve less wind restrictions on the lift, e.g. installing separate blades instead of one assembled rotor, a decrease in the installation duration may be made by up to 30 % (Barlow et al., 2015). Another study done by Dowell et al. (2013) also showed a significant decrease in delay for lifting operations with higher wind restrictions. Considering the high vessel charter rates, delay decrease may in turn contribute to large cost reductions.

Improving vessels to tackle higher winds and waves is therefore a good idea. The Boom Lock developed by the High Wind consortium (High Wind, 2016) is an example of such a technology. The Boom Lock stabilizes components during lifting to create less strict wind limits for performing operation.

2.2.6 *Estimating weather windows*

Weather windows are time intervals when weather conditions are estimated to be such that certain operations can be safely executed.

According to standards for marine operations formulated by DNV (2011), weather restrictions on planned marine operations should be estimated through an *alpha-factor*:

> *[...] The alpha-factor should be calibrated to ensure that the probability of exceeding the operational environmental limiting criteria (OP_{LIM}) with more than* 50% *is less than* 10^{-4} *[...]*

Operational restrictions for feasible and safe operation execution ought to be clearly described. These restrictions are translated into weather restrictions, e.g. maximum wind and wave conditions. Depending on the duration of the planned operation of consideration, the stated weather restrictions and the reliability of the weather forecast, an alpha-factor is suggested.

The alpha-factor scales down the stated weather restrictions by a certain amount to achieve higher certainty of operational success. Tables over alpha-factors have been generated for the North Sea and the Norwegian Sea (DNV, 2011).

Too low estimates of the alpha-factor will cause too narrow weather windows and therefore make operations extremely sensitive. On the other hand, a too high estimate of the alpha-factor may result in severe consequences leading to operation failure and unnecessary costs.

The alpha-factor can create rather conservative weather limitations because restrictions are made only on significant wave height and mean wind speed.

An alternative approach when estimating weather windows has been proposed through the Decision Support for Installation of Offshore Wind Turbines project (DECOFF) (Gintautas et al., 2016), supported by the Norwegian Research Council and Statoil. Equipment responses to different metocean conditions are considered more carefully instead of only taking wind speed and significant wave height limits into account.

By applying more advanced techniques when forecasting weather, uncertainty in the weather forecast can be included without the need of an alpha-factor. The resulting weather window estimation may give a more clear overview of safe operations and possibly prolonged weather windows.

2.3 PREVIOUS WORK

2.3.1 *Mixed integer linear programming (MILP)*

Some mixed integer linear programming models have already been proposed for aiding decisions on installation of offshore wind farms.

Scholz-Reiter et al. (2010) commissioned a model using MILP to optimize offshore assembly with weather conditions taken into account. The model assumes a reliable weather forecast is available. One vessel is used in the installation, and a decision is made on which components to load this vessel with taking into account the weather availability. Further, the installation of each turbine is split into sub-structure and top-structure. The sub-structure has to be installed prior to the top-structure, and the substructure may be built in worse weather than the top-structure. The model by Scholz-Reiter et al. (2010) does not take into consideration the possibility of using several or different vessels, nor probabilistic weather data. The authors suggest extension into a stochastic model.

Ait-Alla et al. (2013) present an aggregated installation problem taking into account different installation vessels able to install different components. Weather conditions are split into five categories where certain installations demand the conditions to be less severe than certain categories. The model seeks to minimize the total installation costs. No decision on which port to use is integrated into the model, and certain constraints make the model non-linear.

Irawan et al. (2015) quite recently assembled a bi-objective combinatorial optimization model to minimize total installation costs and total installation time. Within a deterministic framework, an optimal schedule is estimated using exact method (CPLEX) and meta-heuristic methods (Variable Neighbourhood Search and Simulated Annealing). The model provides an optimal schedule given that predefined vessels do all installation tasks in a certain order. Feasible slots are generated using a separate algorithm taking into account the time it takes to perform the installation tasks, the order in which all tasks must be performed and the weather forecast. The optimization problem then translates into picking feasible slots for when which vessel is to perform which task.

2.3.2 *SINTEF Ocean's model*

The current thesis project has been formulated in cooperation with the company SINTEF Ocean AS. SINTEF Ocean, previously called MARINTEK, is part of the independent research organization SINTEF, and they develop technological solutions for marine industries.

SINTEF Ocean takes part in the LEANWIND project funded by the European Union Seventh Framework Programme. This is a 4-year project being led by a 31-partner consortium. The goal is to apply "lean" principles originating from the car industry to reduce costs in the wind farm life cycle and supply chain.

Prior to this work, the company provided a MILP model from the LEANWIND project with an objective of optimizing wind farm installation with respect to total costs and installation time. The model is similar to the model formulated by Irawan et al. (2015), where separate algorithms are run to produce input. The model by SINTEF Ocean focuses on finding an optimal vessel fleet size and mix instead of scheduling.

The algorithms in SINTEF Ocean's model assume that a vessel type operates in a certain *pattern*. Such a pattern is a defined way of loading and/or installing turbine components for a given vessel type. Patterns generate a certain number of transported and/or installed components after running for a certain time.

As an example, a combined transportation and installation pattern can look like this:

- Load components of certain types and amounts to full capacity.
- Transit to wind farm.
- Jack-up at turbine location.
- Install components.
- Jack-down.
- Transit to next turbine.

- Repeat jack-up, install and jack-down until all components on board are installed.
- Return to port and start reloading.
- Repeat from beginning.

This combined transportation and installation pattern produces both transported and installed components. Patterns can also generate only transported components (transportation patterns) or only installed components (installation patterns).

The patterns are implemented in the model through a cumulative parameter measuring the amount of components transported or installed after a certain amount of time if one vessel type is executing a given pattern. The pattern may be delayed by weather restrictions, and therefore the growth of the cumulative parameter may vary over the time horizon.

The time horizon is defined as a set of discrete time periods. The number of vessels of a given type starting or ending execution of a pattern in a given time period is defined through integer decision variables. The model produces promising results for experiments of up to 125 turbines.

2.3.3 *Alternative modeling*

Lütjen et al. (2012) investigated optimization of a port inventory control system through a simulation approach with a goal of finding an optimized single-echelon inventory system. The result is a reactive scheduling heuristic coordinating the outgoing and incoming components to the main inventory port with respect to a weather forecast. This is an alternative to MILP, and the approach is compared to the model formulated by Scholz-Reiter et al. (2010) with 79 % matching installation times. Equivalently, it is assumed that only one installation vessel performs installations. Operations demanding good weather are preferred and restricted by the availability of components at the main port and the feasibility of installation with respect to other components. The approach may assist in an overall supply chain management to create an efficient inventory management at the main port. A benefit to this method is its ability to scale up to larger scenarios without growing too computationally demanding.

The Norwegian Stavanger-based company Shoreline has developed a simulation tool to tackle the logistical problem of offshore wind farm installations. Their software, SIMSTALL, is based on *agent-based modeling*, and it can be considered a bottom-up approach for creating an installation schedule. The vessels, crew, port and farm site are given as input (agents) into the software with certain constraints and qualities that may depend on each other. The software is then used to analyse the behavior of the system given the behaviour of each individual agent.

2.4 SUMMARY

Limited work has been done on optimization of vessel fleet size and mix during installation of offshore wind farms. As the options for specialized installation vessels grow along with a growing offshore wind farm industry, strategic decisions on installation ports and vessels are more likely to benefit significantly from analytical tool support.

When dealing with the current logistical problem with a MILP model, a challenge is to keep enough assumptions to solve the problem for relevant sizes, but still allow the model to support relevant decisions.

By applying the theory of MILP, two mathematical formulations are suggested in the next chapters to analyse optimization of installation port and fleet with the objective of minimizing total installation costs.

3

MODEL FORMULATION: MODEL 1

A new mixed integer linear programming model, referred to as Model 1, is presented in the following chapter.

In contrast to models suggested by Irawan et al. (2015) and SINTEF Ocean (see Section 2.3.2), the current model does not require separate algorithms to produce input parameters to the model.

The model itself produces the best possible pattern; the idea is that no operation sequences need to be generated beforehand. All options on how or when a vessel is to operate are left open. The choice of which vessels to use is also open. Vessels of the same type may perform different operations at the same time, and they are not restricted to begin chartering simultaneously. This makes the model potentially more computationally demanding. However, more opportunities for how vessels can operate throughout a given time horizon are possible. The component mix and size are not predefined for each vessel type.

The structure of Model 1 is inspired by the *vehicle routing problem (VRP)* (Laporte, 1992). In this problem, one seeks an optimal set of routes for a given amount of vehicles operating from one depot. The vehicles are to serve a given amount of customers and return to the depot. In our case, the vehicles correspond to the operating vessels and the customers correspond to the wind turbine locations. Service is defined as either transporting components to or installing components at the turbine locations.

In Model 1, the idea is to assign vessels to perform all necessary activities without restricting vessels to operate in repeating patterns.

A description of the sets defining Model 1 and their connection to VRP are presented in Section 3.1. How operations are assigned to vessels is described in Section 3.2. The parameters and variables tracking time during the time horizon are presented in Section 3.3, and weather restrictions are introduced in Section 3.4. All modelled costs and the objective function are given in Section 3.5.

3.1 SET DEFINITIONS

3.1.1 *Vessels*

With reference to the VRP, vessels of the same type are modeled as separate vehicles, and these vessels may execute different operations at different times. All vessels are part of the set V:

$$V\text{: Set of vessels}$$

Potential vessels are contained in the set V, and the model supports decisions on which of the vessels to utilize in order to minimize the total costs of installing and transporting turbine components.

Vessels can be categorized by their ability to perform activities:

$$V^T\text{: Set of vessels that can transport components, } V^T \subseteq V$$
$$V^I\text{: Set of vessels that can install components, } V^I \subseteq V$$

The set $V^T \subseteq V$ consists of all vessels that may transport components (*transportation vessels*). Any transportation vessel $v \in V^T \subseteq V$ can load, transport and assist installation of all component types.

Likewise, the set $V^I \subseteq V$ consists of all vessels that may install components (*installation vessels*). Any installation vessel $v \in V^I \subseteq V$ can perform installation of all component types.

All vessels appear in at least one of the two subsets ($V^T \cup V^I = V$). Vessels with the ability to both transport and install components appear in both subsets. Therefore, the model covers instances where $V^T \cap V^I \neq \emptyset$.

3.1.2 *Components and turbine locations*

The operation tasks of all vessels concern transportation and/or installation of certain component types contained in the set D:

$$D = \{d_1, ..., d_{|D|}\}\text{: Set of component types ordered in installation order}$$

The component types are defined in an *ordered* set, because there is a given sequence in which the components must be installed, e.g. substructures before top-structures. One instance of each component type must be installed at all predefined turbine locations.

With reference to the VRP, the turbine locations function as customers demanding all component types to be both transported to and installed at the customer's location. Turbine locations are given in the set R:

$$R\text{: Set of turbine locations}$$

Any transportation vessel $v \in V^T \subseteq V$ can transport components from any port. Any non-installation vessel $v \in V \setminus V^I \subseteq V$ can only transport components and assist installation.

3.1.3 *Ports*

The ports are equivalent to depots in the VRP, thus the model is an extension of the multi-depot VRP (Crevier et al., 2007).

The model does not consider port inventory restrictions, such that any component can be loaded at any time from any port. Potential ports are contained in the set K:

K: Set of ports

Upon achieving a feasible solution, defining which ports to operate from, an overview of which components that need to be available at which port is achieved.

The assumption that no waiting time occurs due to inventory delays is necessary in order to limit the problem to the process of offshore installation of the wind farm.

3.1.4 *Cycles*

Vessels may travel out from and back to a port several times. The largest possible number of such *cycles* for vessel $v \in V$ is represented by the parameter U_v:

U_v: Maximum number of cycles a vessel $v \in V$ can perform throughout the time horizon

With reference to the VRP, these cycles can be interpreted as one vessel representing several vehicles. These vehicles are dependent on each other in the sense that a vehicle corresponding to vessel $v \in V$ on cycle $u \in \{1, ..., U_v - 1\}$ determines when the next vehicle, corresponding to the same vessel $v \in V$ on cycle $u + 1$, can initiate .

The next section introduces constraints and variables representing decision support for assigning operations.

3.2 ASSIGNING OPERATIONS

3.2.1 *Picking vessels and ports*

A feasible solution of the model represents which vessels are in use through the binary variables γ_v:

$$\gamma_v = \begin{cases} 1, & \text{if vessel } v \in V \text{ is mobilized,} \\ 0, & \text{otherwise} \end{cases}$$

All vessels that are mobilized travel through ports. Which ports are in use, and therefore possible to operate from, is represented through the binary variables δ_k:

$$\delta_k = \begin{cases} 1, & \text{if port } k \in K \text{ is in use,} \\ 0, & \text{otherwise} \end{cases}$$

3.2.2 *Routing*

Any transit in between locations on a cycle is identified by the binary variables x_{ijvu}:

$$x_{ijvu} = \begin{cases} 1, & \text{if vessel } v \in V \text{ travels from node } i \in K \cup R \text{ to } j \in K \cup R \ (i \neq j) \\ & \text{on cycle } u \in \{1, \ldots, U_v\}, \\ 0, & \text{otherwise} \end{cases}$$

The variables x_{ijvu} are defined for every pair of turbine and port location except for pairs of the same location.

3.2.3 *Transportation and installation*

The model further supports decisions on which operations chartered vessels are to perform.

Which component type is being transported to which turbine location by which transportation vessel on which cycle, is represented by the binary variables θ_{rdvu}:

$$\theta_{rdvu} = \begin{cases} 1, & \text{if vessel } v \in V^T \subseteq V \text{ is transporting component type } d \in D \\ & \text{to turbine location } r \in R \text{ on cycle } u \in \{1, \ldots, U_v\}, \\ 0, & \text{otherwise} \end{cases}$$

Similarly, installation assignment is identified by the binary variables η_{rdvu}:

$$\eta_{rdvu} = \begin{cases} 1, & \text{if vessel } v \in V^I \subseteq V \text{ is installing component type } d \in D \\ & \text{at turbine location } r \in R \text{ on cycle } u \in \{1, \ldots, U_v\}, \\ 0, & \text{otherwise} \end{cases}$$

3.2.4 *Positioning*

If installation occurs at a turbine location, the vessel performing the installation must *position* at the turbine.

For installation lifts, vessels must commonly jack up. An installation vessel may install several components at the same turbine location during a cycle without exiting its installation position.

After installation of all components are finished at a turbine location, the installation vessel must exit its installation position before it can move on to the next location.

The binary variables ρ_{rvu} keep track of positioning:

$$\rho_{rvu} = \begin{cases} 1, & \text{if vessel } v \in V^I \subseteq V \text{ performs installation of at least one} \\ & \text{component at turbine location } r \in R \text{ on cycle} \\ & u \in \{1,...,U_v\}, \\ 0, & \text{otherwise} \end{cases}$$

These variables are particularly useful for vessel $v \in V^T \cup V^I$ that can both install and transport components. The variables ρ_{rvu} separate turbine visits from entering installation position, thus a vessel $v \in V^T \cup V^I$ can visit a turbine location without entering installation position (if it only transports components).

Next is a presentation of restrictions and constraints related to transportation and installation of components.

3.2.5 *Routing constraints*

In order for a vessel to perform any transits, it must be mobilized:

$$x_{ijvu} \leq \gamma_v, \quad \forall\ i \in K \cup R, j \in K \cup R\ (i \neq j),\ v \in V,\ u \in \{1,...,U_v\} \qquad (3.2.1)$$

Constraints (3.2.1) make sure vessel $v \in V$ can only perform transits in between port or turbine location $i \in K \cup R$ and $j \in K \cup R$ $(i \neq j)$ if vessel $v \in V$ is mobilized.

Vessels can only operate from open ports:

$$\sum_{r \in R} x_{krvu} \leq \delta_k, \qquad \forall\ k \in K,\ v \in V,\ u \in \{1,...,U_v\} \qquad (3.2.2)$$

$$\sum_{r \in R} x_{rkvu} \leq \delta_k, \qquad \forall\ k \in K,\ v \in V,\ u \in \{1,...,U_v\} \qquad (3.2.3)$$

Constraints (3.2.2) ensure that vessel $v \in V$ can only *leave from* port $k \in K$ to some turbine location if port $k \in K$ is open, and constraints (3.2.3) make sure vessel $v \in V$ can only *return to* port $k \in K$ from some turbine location if port $k \in K$ is open.

Constraints (3.2.2) and (3.2.3) also make sure vessel $v \in V$ can only leave from/return to port $k \in K$ to/from only one turbine location on cycle $u \in \{1,...,U_v\}$.

Note that constraints (3.2.1), (3.2.2) and (3.2.3) apply for all cycles $u \in \{1,...,U_v\}$ vessel $v \in V$ can possibly perform.

All vessels can only start a cycle at a port:

$$x_{ijvu} \leq \sum_{k \in K} \sum_{r \in R} x_{krvu},\ \forall\ i \in R,\ j \in R\ (i \neq j),\ v \in V,\ u \in \{1,...,U_v\} \qquad (3.2.4)$$

In (3.2.4), vessel $v \in V$ on cycle $u \in \{1,...,U_v\}$ can only transit in between two turbine locations $i \in R$ and $j \in R$ $(i \neq j)$ if it also leaves some port to some turbine location.

Once a port is left, a vessel must transit through some turbine location(s):

$$\sum_{i\in K\cup R:\, i\neq r} \left(x_{irvu} - x_{rivu}\right) = 0, \qquad \forall\, r \in R,\ v \in V,\ u \in \{1,\ldots,U_v\} \tag{3.2.5}$$

The flow conservation constraints (3.2.5) make sure vessel $v \in V$ must leave all turbine locations $r \in R$ entered on cycle $u \in \{1,\ldots,U_v\}$. As a consequence, a vessel $v \in V$ must eventually return to some port $k \in K$.

If several ports are open, a vessel can only travel out from one of them on every cycle:

$$\sum_{k\in K}\sum_{r\in R} x_{krvu} \leq 1, \qquad \forall\, v \in V,\ u \in \{1,\ldots,U_v\} \tag{3.2.6}$$

Constraints (3.2.6) ensure a vessel $v \in V$ on cycle $u \in \{1,\ldots,U_v\}$ can only leave from one port to one turbine location.

A vessel can only leave the same port it returned to upon starting a new cycle:

$$\sum_{r\in R} x_{krvu} \leq \sum_{r\in R} x_{rkv(u-1)}, \qquad \forall\, k \in K,\ v \in V,\ u \in \{2,\ldots,U_v\} \tag{3.2.7}$$

Constraints (3.2.7) guarantee that a vessel $v \in V$ can only start a new cycle $u \in \{2,\ldots,U_v\}$ from the same port $k \in K$ it returned to on its previous cycle.

3.2.6 *Operational constraints*

With reference to the VRP, the demands of all turbine locations are transportation and installation of all component types:

$$\sum_{v\in V^T}\sum_{u=1}^{U_v} \theta_{rdvu} = 1, \qquad \forall\, r \in R,\ d \in D \tag{3.2.8}$$

$$\sum_{v\in V^I}\sum_{u=1}^{U_v} \eta_{rdvu} = 1, \qquad \forall\, r \in R,\ d \in D \tag{3.2.9}$$

Constraints (3.2.8) make sure component type $d \in D$ is transported to turbine location $r \in R$ by some transportation vessel $v \in V^T \subseteq V$, and constraints (3.2.9) make sure installation of component type $d \in D$ is performed at turbine location $r \in R$ by some installation vessel $v \in V^I \subseteq V$.

Arrival at a turbine location is necessary if a vessel is serving this turbine location on a cycle:

$$\theta_{rdvu} \leq \sum_{i\in K\cup R:\, i\neq r} x_{irvu}, \ \forall\, r \in R,\ d \in D,\ v \in V^T,\ u \in \{1,\ldots,U_v\} \tag{3.2.10}$$

$$\eta_{rdvu} \leq \sum_{i\in K\cup R:\, i\neq r} x_{irvu}, \quad \forall\, r \in R,\ d \in D,\ v \in V^I,\ u \in \{1,\ldots,U_v\} \tag{3.2.11}$$

Through constraints (3.2.10), transportation vessel $v \in V^T \subseteq V$ transporting component type $d \in D$ to turbine $r \in R$ must transit there on cycle $u \in \{1,\ldots,U_v\}$.

Likewise, constraints (3.2.11) make sure an installation vessel transits to the turbine location where installation is executed.

Before installation can begin, the installation vessel must position for installation:

$$\eta_{rdvu} \leq \rho_{rvu}, \qquad \forall\ r \in R,\ d \in D,\ v \in V^I,\ u \in \{1, ..., U_v\} \tag{3.2.12}$$

Constraints (3.2.12) will assign the variables ρ_{rvu} with value 1 if installation vessel $v \in V^I \subseteq V$ on cycle $u \in \{1, ..., U_v\}$ performs installation of any component type $d \in D$ at turbine location $r \in R$.

3.2.7 *Loading restrictions*

The loading restrictions on each cycle for transportation vessel $v \in V^T \subseteq V$ are given through capacity parameters z_v and component weight parameters w_d:

z_v: Transportation capacity of vessel $v \in V^T \subseteq V$

w_d: Weight of component type $d \in D$

A transportation vessel may load different components for its cycles as long as the total weight does not exceed the vessel's loading capacity:

$$\sum_{r \in R} \sum_{d \in D} \theta_{rdvu} w_d \leq z_v, \qquad \forall\ v \in V^T,\ u \in \{1, ..., U_v\} \tag{3.2.13}$$

Constraints (3.2.13) ensure the sum of all component weights on a cycle $u \in \{1, ..., U_v\}$ does not exceed the loading capacity of transportation vessel $v \in V^T \subseteq V$.

Note that transportation vessel $v \in V^T \subseteq V$ may load differently on each cycle.

3.3 TIME TRACKING

3.3.1 *Continuous time*

Unlike SINTEF Ocean's model, presented in Section 2.3.2, where time is modelled deterministically as a set of time periods, the current alternative model defines time *continuously*. This means the total time available is only given as a parameter P (not a set of periods):

P: Length of time horizon

All variables concerning the time at which operations take place are defined separately from the variables concerning operation assignment. This creates less dimensions for the variable vectors by avoiding the time index. As a consequence, less memory is needed when running an algorithm to find a good or optimal solution.

The timing of vessel operations is represented by continuous time variables. A presentation of time variables and related constraints are given next.

3.3.2 *Cycle time*

For a vessel $v \in V$, the start and end times of cycle $u \in \{1,...,U_v\}$ are represented by the continuous variables q_{vu} and e_{vu}:

$q_{vu} \in \mathbb{R}_+$: Time when vessel $v \in V$ starts cycle $u \in \{1,...,U_v\}$
$e_{vu} \in \mathbb{R}_+$: Time when vessel $v \in V$ ends cycle $u \in \{0,...,U_v\}$

Note that e_{vu} is also defined for $u = 0$. Thus, e_{vu} can be interpreted as the time loading of vessel $v \in V^T \in V$ starts on cycle $u+1$.

Each component type $d \in D$ takes a certain amount of time t_d^L to load independent of vessel $v \in V^T \subseteq V$:

t_d^L: Time needed to load component type $d \in D$

With the parameter t_d^L, loading time for vessel $v \in V^T$ can be expressed as constraints:

$$e_{v(u-1)} + \sum_{r\in R}\sum_{d\in D} t_d^L \theta_{rdvu} \leq q_{vu}, \ \forall\ v \in V^T,\ u \in \{1,...,U_v\} \tag{3.3.1}$$

$$e_{v(u-1)} \leq q_{vu}, \ \forall\ v \in V \backslash V^T,\ u \in \{1,...,U_v\} \tag{3.3.2}$$

Constraints (3.3.1) make sure a vessel $v \in V^T \subseteq V$ cannot start a cycle before loading is complete. Furthermore, (3.3.1) and (3.3.2) make sure vessel $v \in V$ cannot start a new cycle before the previous cycle ended.

Parameters define durations of possible transits, durations of jack-up/jack-down and durations of installation:

t_{ijv}^T: Time to transit vessel $v \in V$ in between port or turbine location $i \in K \cup R$ and port or turbine location $j \in K \cup R$ $(i \neq j)$
t_v^{PJ}: Time to jack-up/jack-down vessel $v \in V \subseteq V$
t_{dv}^I: Time to install component type $d \in D$ with vessel $v \in V^I \subseteq V$
t_{dv}^A: Time to assist installation of component type $d \in D$ with vessel $v \in V^T \subseteq V$

Throughout the charter period of vessel $v \in V$, certain moments in time are defined as continuous variables:

$s_{rvu} \in \mathbb{R}_+$: Time when vessel $v \in V$ arrives at turbine $r \in R$ on cycle $u \in \{1,...,U_v\}$
$g_{rvu} \in \mathbb{R}_+$: Time when vessel $v \in V^I \subseteq V$ starts jacking down at turbine $r \in R$ on cycle $u \in \{1,...,U_v\}$
$h_{rvu} \in \mathbb{R}_+$: Time when vessel $v \in V$ leaves turbine $r \in R$ on cycle $u \in \{1,...,U_v\}$
$f_{rd} \in \mathbb{R}_+$: Time when installation of component type $d \in D$ starts at turbine location $r \in R$

Even though the continuous time variables s_{rvu} and h_{rvu} are defined for every turbine location $r \in R$ and every possible cycle $u \in \{1,...,U_v\}$ for vessel $v \in V$, these variables are only assigned meaningful values for locations visited. Note that the variables g_{rvu} are only defined for installation vessels.

Vessel $v \in V$ arrives at turbine $r \in R$ after leaving port $k \in K$:

$$q_{vu} + t^{T}_{krv} - P(1 - x_{krvu}) \leq s_{rvu}, \ \forall \ k \in K, r \in R, \ v \in V, \ u \in \{1,...,U_v\} \tag{3.3.3}$$

Constraints (3.3.3) make sure vessel $v \in V$ cannot arrive at turbine $r \in R$ on cycle $u \in \{1,...,U_v\}$ before the transit from port $k \in K$ has ended. Constraints (3.3.3) are only constraining if vessel $v \in V$ leaves from port $k \in K$ to turbine $r \in R$ on cycle $u \in \{1,...,U_v\}$, that is if $x_{krvu} = 1$.

Installation at turbine $r \in R$ can start after vessel $v \in V$ performing or assisting installation has arrived:

$$s_{rvu} - P(1 - \theta_{rdvu}) \leq f_{rd}, \ \forall \ r \in R, \ d \in D, \ v \in V^T, \ u \in \{1,...,U_v\} \tag{3.3.4}$$

$$s_{rvu} + t^{PJ}_{v} - P(1 - \eta_{rdvu}) \leq f_{rd}, \ \forall \ r \in R, \ d \in D, \ v \in V^I, \ u \in \{1,...,U_v\} \tag{3.3.5}$$

Constraints (3.3.4) make sure transportation vessel $v \in V^T \subseteq V$ arrives at turbine $r \in R$ before installation of component type $d \in D$ can begin (if $\theta_{rdvu} = 1$).

Constraints (3.3.5) ensure installation vessel $v \in V^I \subseteq V$ arrives and enters installation position at turbine $r \in R$ before installation of component type $d \in D$ can start (if $\eta_{rdvu} = 1$).

Components must be installed in a defined order at each turbine:

$$f_{rd_{m-1}} + \sum_{v \in V^I} \sum_{u=1}^{U_v} \eta_{rd_{m-1}vu} t^{I}_{d_{m-1}v} \leq f_{rd_m}, \qquad \forall \ r \in R, \ m \in 2,...,|D| \tag{3.3.6}$$

Constraints (3.3.6) make sure installation of component type $d_{m-1} \in D$ is complete before installation of the successive component type $d_m \in D$ can begin at turbine $r \in R$. Note that installation of two consecutive component types can happen with different installation vessels.

Transportation vessels must assist installation at turbine $r \in R$ for a certain amount of time after installation of component type $d \in D$ has started:

$$f_{rd} + t^{A}_{dv} - P(1 - \theta_{rdvu}) \leq h_{rvu}, \ \forall \ r \in R, \ d \in D, \ v \in V^T, \ u \in \{1,...,U_v\} \tag{3.3.7}$$

Constraints (3.3.7) make sure transportation vessel $v \in V^T \subseteq V$ finish assisting installation of component type $d \in D$ at turbine $r \in R$ before leaving.

Similar constraints apply for installation vessels:

$$f_{rd} + t^{I}_{dv} - P(1 - \eta_{rdvu}) \leq g_{rvu}, \ \forall \ r \in R, \ d \in D, \ v \in V^I, \ u \in \{1,...,U_v\} \tag{3.3.8}$$

$$g_{rvu} + t^{PJ}_{v} - P(1 - \rho_{rvu}) \leq h_{rvu}, \ \forall \ r \in R, \ v \in V^I, \ u \in \{1,...,U_v\} \tag{3.3.9}$$

Constraints (3.3.8) and (3.3.9) make sure installation vessel $v \in V^I \subseteq V$ finish installation of component type $d \in D$ at turbine $r \in R$ and jacks down before leaving.

After leaving turbine $r \in R$ on cycle $u \in \{1,...,U_v\}$, vessel $v \in V$ either transits to another turbine or back to a port:

$$h_{ivu} + t^T_{ijv} - P(1 - x_{ijvu}) \leq s_{jvu}, \ \forall \ i \in R, \ j \in R \ (i \neq j), \ v \in V, \ u \in \{1,...,U_v\} \tag{3.3.10}$$

$$h_{rvu} + t^T_{rkv} - P(1 - x_{rkvu}) \leq e_{vu}, \ \forall \ k \in K, \ r \in R, \ v \in V, \ u \in \{1,...,U_v\} \tag{3.3.11}$$

Constraints (3.3.10) and (3.3.11) track time for assigned transits to vessel $v \in V$ through the binary routing variables x_{ijvu}.

The model also needs to track time for potential turbine visits where no operation is assigned vessel $v \in V$:

$$s_{rvu} \leq h_{rvu}, \ \forall \ r \in R, \ v \in V, \ u \in \{1,...,U_v\} \tag{3.3.12}$$

Constraints (3.3.12) make sure vessel $v \in V$ on cycle $u \in \{1,...,U_v\}$ cannot leave before arriving at turbine $r \in R$. Constraints (3.3.12) are necessary to eliminate the feasibility of solutions where time is not tracked.

All cycles must be finished before the time horizon:

$$e_{vu} \leq P, \quad \forall \ v \in V, \ u \in \{0,...,U_v\} \tag{3.3.13}$$

Constraints (3.3.13) say that vessel $v \in V$ cannot return to a port after time P.

Total length of the charter period for vessel $v \in V$ is represented by continuous variables E_v:

$E_v \in \mathbb{R}_+$: Total time vessel $v \in V$ is chartered

Charter length of vessel $v \in V$ is measured from the vessel starts operation until it returns to port:

$$e_{vu} - e_{v0} \leq E_v, \quad \forall \ v \in V, \ u \in \{1,...,U_v\} \tag{3.3.14}$$

Constraints (3.3.14) make sure the total charter period of vessel $v \in V$ is at least as long as the time when operations are performed.

Next is a presentation on how weather restrictions are considered in the current model.

3.4 WEATHER WINDOWS

Weather windows are introduced as time intervals when certain operations can occur. Weather restrictions are considered for transiting, positioning and installation of turbines.

Weather restrictions in the current model can only be based on deterministic data, i.e. weather forecasts or historical weather data for site specific analysis.

With weather data available, weather windows can be estimated as time intervals where an activity can successfully be performed. Uncertainty in the weather forecast can be considered through one of the methods described in Section 2.2.6.

There can be several weather windows for the same operation throughout the time horizon.

3.4.1 *Weather window parameters*

The number of weather windows for transiting, positioning and installation are given as vessel dependent integer parameters W_v^T, W_v^{PJ} and W_{dv}^I respectively:

W_v^T: Number of weather windows for transiting with vessel $v \in V$
W_v^{PJ}: Number of weather windows for positioning vessel $v \in V^I \subseteq V$
W_{dv}^I: Number of weather windows for installing components of type $d \in D$ with vessel $v \in V^I \subseteq V$

For each vessel $v \in V$, there are W_v^T number of non-overlapping weather windows where any transit can be made.

Similarly, there are W_v^{PJ} number of weather windows where vessel $v \in V^I \subseteq V$ can position for installation and W_{dv}^I weather windows where installation of component type $d \in D$ can be performed by vessel $v \in V^I \subseteq V$.

Each weather window has a start and an end:

a_{vn}^T: Start of weather window $n \in \{1, \ldots, W_v^T\}$ for transit with vessel $v \in V$
b_{vn}^T: End of weather window $n \in \{1, \ldots, W_v^T\}$ for transit with vessel $v \in V$
a_{vn}^{PJ}: Start of weather window $n \in \{1, \ldots, W_v^{PJ}\}$ for setup with vessel $v \in V^I \subseteq V$
b_{vn}^{PJ}: End of weather window $n \in \{1, \ldots, W_v^{PJ}\}$ for setup with vessel $v \in V^I \subseteq V$
a_{dvn}^I: Start of weather window $n \in \{1, \ldots, W_{dv}^I\}$ for installing components of type $d \in D$ with vessel $v \in V^I \subseteq V$
b_{dvn}^I: End of weather window $n \in \{1, \ldots, W_{dv}^I\}$ for installing components of type $d \in D$ with vessel $v \in V^I \subseteq V$

The parameters listed above represent the moment in time at which a weather window opens and closes.

3.4.2 *Weather window restrictions*

Weather restricted activities must be performed within one of the predefined weather windows. Representing the choices of windows, we introduce the following binary weather window decision variables:

$$N^{T}_{ijvun} = \begin{cases} 1, & \text{if vessel } v \in V \text{ transits from location } i \in K \cup R \text{ to } j \in K \cup R \ (i \neq j) \\ & \text{on cycle } u \in \{1, ..., U_v\} \text{ in weather window } n \in \{1, ..., W^T_v\}, \\ 0, & \text{otherwise} \end{cases}$$

$$N^{PJ1}_{rvun} = \begin{cases} 1, & \text{if vessel } v \in V^I \subseteq V \text{ enters installation position at turbine } r \in R \\ & \text{on cycle } u \in \{1, ..., U_v\} \text{ in weather window } n \in \{1, ..., W^{PJ}_v\}, \\ 0, & \text{otherwise} \end{cases}$$

$$N^{PJ2}_{rvun} = \begin{cases} 1, & \text{if vessel } v \in V^I \subseteq V \text{ exits installation position at turbine } r \in R \\ & \text{on cycle } u \in \{1, ..., U_v\} \text{ in weather window } n \in \{1, ..., W^{PJ}_v\}, \\ 0, & \text{otherwise} \end{cases}$$

$$N^{I}_{rdvn} = \begin{cases} 1, & \text{if component type } d \in D \text{ at turbine location } r \in R \\ & \text{is installed by vessel } v \in V^I \subseteq V \text{ in weather} \\ & \text{window } n \in \{1, ..., W^I_{dv}\}, \\ 0, & \text{otherwise} \end{cases}$$

The binary variables defined above identify in which weather window operations are performed. Note that jack-up and jack-down may take place in two different weather windows for vessel $v \in V^I \subseteq V$ at the same turbine $r \in R$.

Vessel $v \in V$ only transits between certain locations:

$$\sum_{n=1}^{W^T_v} N^T_{ijvun} = x_{ijvu}, \ \forall \ i \in K \cup R, \ j \in K \cup R \ (i \neq j), \ v \in V, \ u \in \{1, ..., U_v\} \tag{3.4.1}$$

Constraints (3.4.1) make sure all transits made by vessel $v \in V$ are made within a weather window $n \in \{1, ..., W^T_v\}$.

Analogously to constraints (3.4.1), jack-up, jack-down and installation must occur within their respective weather windows:

$$\sum_{n=1}^{W^{PJ}_v} N^{PJ1}_{rvun} = \rho_{rvu}, \quad \forall \ r \in R, \ v \in V^I, \ u \in \{1, ..., U_v\} \tag{3.4.2}$$

$$\sum_{n=1}^{W^{PJ}_v} N^{PJ2}_{rvun} = \rho_{rvu}, \quad \forall \ r \in R, \ v \in V^I, \ u \in \{1, ..., U_v\} \tag{3.4.3}$$

$$\sum_{v \in V^I} \sum_{n=1}^{W^I_d} N^I_{rdvn} = 1, \quad \forall \ r \in R, \ d \in D \tag{3.4.4}$$

Constraints (3.4.2) and (3.4.3) ensure a weather window is used for jack-up and jack-down if vessel $v \in V$ positions at turbine $r \in R$ on cycle $u \in$

$\{1,...,U_v\}$. Constraints (3.4.4) make sure all installations happen within a weather window.

The time at which operations are executed must fit within a weather window. The timing when vessel $v \in V$ transits from port to turbine $r \in R$ on cycle $u \in \{1,...,U_v\}$ is restricted by the choice of weather window:

$$\sum_{k\in K}\sum_{r\in R}\sum_{n=1}^{W_v^T} N_{krvun}^T a_{vn}^T \leq q_{vu}, \ \forall\ v \in V,\ u \in \{1,...,U_v\} \tag{3.4.5}$$

$$q_{vu} + \sum_{k\in K}\sum_{r\in R} x_{krvu} t_{krv}^T \leq \sum_{k\in K}\sum_{r\in R}\sum_{n=1}^{W_v^T} N_{krvun}^T b_{vn}^T, \ \forall\ v \in V,\ u \in \{1,...,U_v\} \tag{3.4.6}$$

Constraints (3.4.5) and (3.4.6) make sure the first transit by vessel $v \in V$ on cycle $u \in \{1,...,U_v\}$ happens within the weather window identified by the binary variable N_{krvun}^T.

Likewise, other transits must happen within a weather window:

$$\sum_{n=1}^{W_v^T} N_{ijvun}^T a_{vn}^T \leq h_{ivu}, \qquad \forall\ i \in R,\ j \in K \cup R\ (i \neq j),\ v \in V,\ u \in \{1,...,U_v\} \tag{3.4.7}$$

$$h_{ivu} + t_{ijv}^T - P(1 - x_{ijvu}) \leq \sum_{n=1}^{W_v^T} N_{ijvun}^T b_{vn}^T, \quad \forall\ i \in R,\ j \in K \cup R\ (i \neq j),\ v \in V,\ u \in \{1,...,U_v\} \tag{3.4.8}$$

Constraints (3.4.7) and (3.4.8) covers all transits from any turbine $i \in R$, and, in a similar way to constraints (3.4.5) and (3.4.6), make sure the respective transit time fits within the chosen weather window interval.

The moments in time at which jack-up and jack-down occurs are restricted by weather windows:

$$\sum_{n=1}^{W_v^{PJ}} N_{rvun}^{PJ1} a_{vn}^{PJ} \leq s_{rvu}, \quad \forall\ r \in R,\ v \in V^I,\ u \in \{1,...,U_v\} \tag{3.4.9}$$

$$s_{rvu} + t_v^{PJ} - P(1 - \rho_{rvu}) \leq \sum_{n=1}^{W_v^{PJ}} N_{rvun}^{PJ1} b_{vn}^{PJ}, \ \forall\ r \in R,\ v \in V^I,\ u \in \{1,...,U_v\} \tag{3.4.10}$$

$$\sum_{n=1}^{W_v^{PJ}} N_{rvun}^{PJ2} a_{vn}^{PJ} \leq g_{rvu}, \ \forall\ r \in R,\ v \in V^I,\ u \in \{1,...,U_v\} \tag{3.4.11}$$

$$g_{rvu} + t_v^{PJ} - P(1 - \rho_{rvu}) \leq \sum_{n=1}^{W_v^{PJ}} N_{rvun}^{PJ2} b_{vn}^{PJ}, \ \forall\ r \in R,\ v \in V^I,\ u \in \{1,...,U_v\} \tag{3.4.12}$$

Constraints (3.4.9)-(3.4.12) make sure jack-up/jack-down happens during assigned weather windows.

Finally, installation is also restricted by weather:

$$\sum_{v\in V^I}\sum_{n=1}^{W_d^I} N_{rdvn}^I a_{dvn}^I \leq f_{rd}, \qquad \forall\ r\in R,\ d\in D \tag{3.4.13}$$

$$f_{rd} + \sum_{v\in V^I}\sum_{u=1}^{U_v} \eta_{rdvu} t_{dv}^I \leq \sum_{v\in V^I}\sum_{n=1}^{W_d^I} b_{dvn}^I N_{rdvn}^I, \qquad \forall\ r\in R,\ d\in D \tag{3.4.14}$$

Constraints (3.4.13) and (3.4.14) ensure all components are installed within their given weather window interval.

The next section presents cost parameters and the objective function regarding total costs.

3.5 OBJECTIVE FUNCTION

There are costs related to ports and vessels, and operational costs related to vessel activities.

A fixed cost is defined for the use of port $k \in K$ during the time horizon:

c_k^K: Fixed cost of operating from port $k \in K$

There is a fixed cost for mobilizing and chartering vessel $v \in V$:

c_v^{TC}: Time charter cost per time unit for vessel $v \in V$
c_v^M: Mobilization cost for starting chartering of vessel $v \in V$

All the following operational costs are related to fuel consumption during certain operations. Operational costs are defined for vessels as costs per time unit.

There are different costs related to loading, installing, transiting and positioning:

c_v^L: Cost per time unit for loading vessel $v \in V^T \subseteq V$
c_v^I: Cost per time unit for performing installation with vessel $v \in V^I \subseteq V$
c_v^T: Cost per time unit for transiting vessel $v \in V$
c_v^{PJ}: Cost per time unit for positioning vessel $v \in V^I \subseteq V$

Note that there are no operational costs related to assisting installation for transportation vessel $v \in V^T \subseteq V$, but penalty is still given through the running time charter cost. Weather delays are penalized in the same manner.

The objective of the model is to minimize the total logistical costs of offshore installation. The objective function needs to define total costs:

$$\begin{aligned}\min \sum_{k\in K} c_k^F \delta_k + \sum_{v\in V}\left(c_v^{SC}\gamma_v + c_v^{TC}E_v\right) + \\ \sum_{r\in R}\sum_{d\in D}\sum_{u=1}^{U_v}\left(\sum_{v\in V^T} c_v^L t_d^L \theta_{rdvu} + \sum_{v\in V^I} c_v^I t_{vd}^I \eta_{rdvu}\right) + \\ \sum_{i\in K\cup R}\ \sum_{j\in K\cup R:\ i\neq j}\ \sum_{v\in V}\sum_{u=1}^{U_v} c_v^T t_{ijv}^T x_{ijvu} + \sum_{r\in R}\sum_{v\in V^I}\sum_{u=1}^{U_v} 2c_v^{PJ} t_v^{PJ} \rho_{rvu}\end{aligned} \tag{3.5.1}$$

The first three terms in (3.5.1) reflect port and vessel costs. These costs are identified through the binary port decision variables δ_k, the binary vessel decision variables γ_v and the continuous time charter variables E_v.

The next term in (3.5.1) reflects total operational costs related to loading through the binary transport variables θ_{rdvu}. The fifth term measures operational installation costs through the binary installation variables η_{rdvu}.

The sixth term in (3.5.1) identifies operational transit costs through the routing variables x_{ijvu}, and the last term adds operational costs related to jack-up and jack-down through the binary positioning variables ρ_{rvu}.

3.6 SUMMARY

A complete mathematical formulation of the model presented in Chapter 3 is presented in Appendix A.

The model formulated in Chapter 3 is a generalisation of the VRP. It is recognized that the VRP is an NP-hard problem, with the trait that no algorithms are known to solve the problem exactly in polynomial time. Running the model for data sets of interesting size is rather optimistic in terms of finding an optimal or even a feasible solution.

Model 1 has been implemented in AMPL with small data sets. The model deliver promising feasible solutions for small instances using the CPLEX solver.

However, the branch and bound algorithm start to struggle as the size of the problem grows. Even with 4 vessels, 2 ports, 10 turbines and 2 component types, not even a feasible solution for the problem can be obtained using the CPLEX solver within a reasonable utilization of computer time and memory.

The next chapter introduces a simplified version of Model 1.

4

MODEL SIMPLIFICATION: MODEL 2

A simplified version of Model 1 described in Chapter 3 is presented in the following chapter, and this model is referred to as Model 2.

The underlying idea is consistent with Model 1, but the following simplifications are made:

- Routing in between turbines is omitted (see Section 4.1.1).
- Vessels must transport and install entire turbines (see Section 4.1.2).

4.1 SIMPLIFICATIONS

4.1.1 *Omitting routing*

The trend in offshore wind farms moves toward an increased distance from shore to farm. As a consequence, vehicle routing may becomes less relevant in between turbines if the farm does not span very large areas. A simplified structure of the problem is obtained by not considering routing in between turbines.

In contrast to the model formulated in Chapter 3, the travel time in between turbines may be given as a fixed parameter only dependent on the vessel in use. By only considering routing in between port and wind farm as a whole, the computational challenge of the model is significantly reduced.

4.1.2 *Limiting choices of installation*

A common practice in the industry is to install complete wind turbines at each turbine location after sub-structures and cables are in place. By assuming one vessel installs all components at a turbine location, each turbine component does not need to be considered explicitly, and thus the model is further simplified.

4.2 REDEFINING SETS

4.2.1 *Vessel strategies*

Since components are not considered explicitly, vessel decisions also represent how to handle components.

Possible *vessel strategies* make up the set V:

$$V\text{: Set of vessel strategies}$$

The main difference between the vessel strategies in Model 2 and the individual vessels in Model 1, is that Model 2 does not distinguish between transportation and installation vessels.

A vessel strategy consists of one or several vessels performing repeating installation sequences. In contrast to Model 1, the vessels are assumed to only perform operations leading to complete installation of each visited turbine, and each turbine is installed with exactly one strategy $v \in V$. Vessel strategy $v \in V$ might represent several vessels, e.g. one installation vessel supported by one transportation vessel.

An example of a vessel strategy can be a "transiting" strategy (see Section 2.2.3): One vessel loads a certain amount of complete turbines in a certain configuration, installs them all in sequence and returns to port. The only decision left open is how many complete turbines (not individual components) the vessel(s) load and install on each cycle.

4.2.2 *Vessel strategy duplication*

Vessel strategy $v \in V$ may be implemented twice or more in the same data set (with the same parameters). This *strategy duplication* allows several vessels to operate with the same strategy. For example, a solution may be to use a certain "transiting" strategy with two vessels transporting and installing turbines in the same way. If strategy $v \in V$ is duplicated, vessels of the duplicated strategies do not necessarily operate simultaneously.

More examples of specific vessel strategies are defined in Section 5.3.

4.2.3 *Cycles and ports*

Equivalent to the model formulated in Chapter 3, the potential ports constitute the set K (see Section 3.1.3), and the maximum amount of cycles vessel strategy $v \in V$ can perform is given as a parameter U_v (see Section 3.1.4)

K: Set of ports

U_v: Maximum number of cycles possible with vessel strategy $v \in V$

4.2.4 *Turbines*

Because the simplified model considers all turbines to be located in the wind farm with fixed distance from ports, the total amount of turbines is defined as one parameter R (instead of a set of turbines):

$$R\text{: Total number of wind turbines}$$

Transportation and installation of one turbine is done with exactly one vessel strategy.

There is an upper bound Y_v on how many turbines that may be loaded with strategy $v \in V$ per cycle:

Y_v: Maximum number of turbines installed per cycle with vessel strategy $v \in V$

The loading capacity of vessel strategy $v \in V$ is represented through the parameter Y_v.

All loaded turbines must be installed on the same cycle. The option of not loading and installing the maximum possible number of turbines per cycle exists, and this option is relevant in several cases, e.g. bad weather availability for strategy $v \in V$.

The next section redefines certain decision variables and constraints for the simplified model structure.

4.3 REDEFINING DECISION VARIABLES AND CONSTRAINTS

Some decision variables are equivalent to the variables in Model 1 (formulated in Section 3.2):

$$\delta_k = \begin{cases} 1, & \text{if port } k \in K \text{ is in use,} \\ 0, & \text{otherwise} \end{cases}$$

$$\gamma_v = \begin{cases} 1, & \text{if vessel strategy } v \in V \text{ is chosen,} \\ 0, & \text{otherwise} \end{cases}$$

Other decision variables are redefined with fewer indices in the following sections.

4.3.1 *Redefining decision variables*

Vessel strategy $v \in V$ is assigned a port $k \in K$ to operate from on cycle $u \in \{1,...,U_v\}$ represented through the binary variable x_{kvu}:

$$x_{kvu} = \begin{cases} 1, & \text{if vessel strategy } v \in V \text{ is run from port } k \in K \\ & \text{on } u \in \{1,...,U_v\} \text{ or more cycles,} \\ 0, & \text{otherwise} \end{cases}$$

The variables x_{kvu} replace the routing variables x_{ijvu} from the model in Chapter 3.

The decision on transporting and installing $y \in \{1,...,Y_v\}$ turbines with vessel strategy $v \in V$ on cycle $u \in \{1,...,U_v\}$ are represented through the binary variable θ_{vuy}:

$$\theta_{vuy} = \begin{cases} 1, & \text{if vessel strategy } v \in V \text{ runs } u \in \{1,...,U_v\} \text{ or more cycles} \\ & \text{installing } y \in \{1,...,Y_v\} \text{ or more turbines,} \\ 0, & \text{otherwise} \end{cases}$$

The variables θ_{vuy} replace the variables θ_{rdvu} and η_{rdvu} from the model in Chapter 3.

The positioning variables ρ_{rvu} from Model 1 are unnecessary in the current simplified model, since all turbine visits require an installation vessel part of vessel strategy $v \in V$ to enter installation position.

4.3.2 *Redefining assignment*

All turbines must be mounted:

$$\sum_{v \in V} \sum_{u=1}^{U_v} \sum_{y=1}^{Y_v} \theta_{vuy} \geq R \tag{4.3.1}$$

Constraint (4.3.1) ensures all turbines are transported and installed with some vessel strategy $v \in V$.

Some strategies must be used and some ports must be open:

$$\theta_{vuy} \leq \gamma_v, \quad \forall\ v \in V,\ u \in \{1,...,U_v\},\ y \in \{1,...,Y_v\} \tag{4.3.2}$$

$$x_{kvu} \leq \delta_k, \quad \forall\ k \in K,\ v \in V,\ u \in \{1,...,U_v\} \tag{4.3.3}$$

Constraints (4.3.2) make sure strategy $v \in V$ can only be used if mobilized, and (4.3.3) make sure port $k \in K$ can only be used if opened.

Vessel strategy $v \in V$ operates from only one port each cycle:

$$\sum_{k \in K} x_{kvu} \leq 1, \qquad \forall\ v \in V, u \in \{1,...,U_v\} \tag{4.3.4}$$

Constraints (4.3.4) make sure strategy $v \in V$ is run from only one port on cycle $u \in \{1,...,U_v\}$.

A vessel strategy must be assigned a port:

$$\theta_{vu1} \leq \sum_{k \in K} x_{kvu},\ \forall\ v \in V,\ u \in \{1,...,U_v\} \tag{4.3.5}$$

Constraints (4.3.5) make sure vessel strategy $v \in V$ starts cycle $u \in \{1,...,U_v\}$ from a port if at least one turbine is installed.

4.3.3 *Special ordered sets of type 2 (SOS2)*

Because port transits with strategy $v \in V$ are independent of individual turbines, the use of different ports with the same strategy $v \in V$ cannot be optimal. A strategy $v \in V$ is therefore assigned one port $k \in K$ to operate from throughout the entire time horizon:

$$x_{kvu} \leq x_{kv(u-1)}, \qquad \forall\ k \in K,\ v \in V,\ u \in \{2,...,U_v\} \tag{4.3.6}$$

Constraints (4.3.6) ensure strategy $v \in V$ continues to run from no other port than port $k \in K$ where it started operation.

With constraints (4.3.6), the variables x_{kvu} where $u \in \{1,...,U_v\}$ form a *special ordered set* of type 2 (SOS2) (Beale and Tomlin, 1970). An SOS2 is a set of non-negative variables, where two adjacent variables may be non-zero, and all values in the case of non-zero adjacency are consecutive. This means that for strategy $v \in V$ on cycle $u^* \in \{1,...,U_v\}$ operating from port $k \in K$, we have that:

- $x_{kvu^*} = 1 \Leftrightarrow x_{kvu} = 1, \ \forall \ u \in \{1,..,u^*\}$, and

- $x_{kvu^*} = 0 \Leftrightarrow x_{kvu} = 0, \ \forall \ u \in \{u^*,...,U_v\}$.

The decision variables θ_{vuy} where $y \in \{1,...,Y_v\}$ and $u \in \{1,...,U_v\}$ also form special ordered sets of type 2 through the following constraints:

$$\theta_{vuy} \leq \theta_{vu(y-1)}, \ \forall \ v \in V, \ u \in \{1,...,U_v\}, \ y \in \{2,...,Y_v\} \tag{4.3.7}$$

$$\theta_{vuy} \leq \theta_{v(u-1)1}, \ \forall \ v \in V, \ u \in \{2,...,U_v\}, \ y \in \{1,...,Y_v\} \tag{4.3.8}$$

Constraints (4.3.7) ensure $y \in \{2,...,Y_v\}$ turbines can only be installed with strategy $v \in V$ if $y-1$ turbines are also installed on cycle $u \in \{1,...,U_v\}$.

Constraints (4.3.8) ensure $u \in \{2,...,U_v\}$ cycles can only be made with strategy $v \in V$ if $u-1$ cycles are made where at least one turbine is installed.

The properties of SOS2 are useful when running a branch and bound algorithm in search of an optimal solution.

4.4 REDEFINING TIME RESTRICTIONS

4.4.1 *Redefining time variables and parameters*

Operation durations are given as time parameters:

t_v^L: Time needed to load one turbine with vessel strategy $v \in V$
t_v^I: Time to install a turbine with vessel strategy $v \in V$
t_v^T: Time for turbine transits with vessel strategy $v \in V$
t_v^{PJ}: Time to jack-up/jack-down with vessel strategy $v \in V$
t_{kv}^K: Time for port transits from port $k \in K$ with vessel strategy $v \in V$

Note that installation duration parameters t_v^I and loading duration parameters t_v^L are not indexed over components, but assumed to be equal for strategy $v \in V$ for each complete turbine.

The transit parameters t_{kv}^K and t_v^T are only dependent on vessel strategy $v \in V$ and port $k \in K$. This leads to a great reduction in the computational challenge from Model 1, where the transit parameters t_{ijv}^T are node dependent (see Section 3.3.2).

Continuous time variables define the same moments in time as in Chapter 3:

$q_{vu} \in \mathbb{R}_+$: Time when vessel cycle $u \in \{1,...,U_v\}$ starts with strategy $v \in V$

$e_{vu} \in \mathbb{R}_+$: Time when cycle $u \in \{0,...,U_v\}$ ends with strategy $v \in V$

$s_{vuy} \in \mathbb{R}_+$: Time when jack-up at turbine $y \in \{1,...,Y_v\}$ starts with strategy $v \in V$ on cycle $u \in \{1,...,U_v\}$

$f_{vuy} \in \mathbb{R}_+$: Time when installation of turbine $y \in \{1,...,Y_v\}$ starts with strategy $v \in V$ on cycle $u \in \{1,...,U_v\}$

$g_{vuy} \in \mathbb{R}_+$: Time when jack-down at turbine $y \in \{1,...,Y_v\}$ starts with strategy $v \in V$ on cycle $u \in \{1,...,U_v\}$

$h_{vuy} \in \mathbb{R}_+$: Time when transit away from turbine $y \in \{1,...,Y_v\}$ starts with strategy $v \in V$ on cycle $u \in \{1,...,U_v\}$

The main difference from Model 1 is the change in the continuous time variables for installation f_{vuy}. These variables are not indexed for each component in Model 2, but for one complete wind turbine.

4.4.2 *Redefining cycle time*

With respect to time tracking, the parameters S_v, F_v, and H_v are introduced:

$$\begin{aligned} S_v &= P - t_v^I - t_v^{PJ} - \min_{k\in K}\{t_{kv}^K\} \\ F_v &= P - t_v^{PJ} - \min_{k\in K}\{t_{kv}^K\} \\ H_v &= P - \min_{k\in K}\{t_{kv}^K\} \end{aligned}$$

These parameters replace the upper bound P in certain constraints concerning time tracking.

For instance, S_v is the maximum possible value for the continuous time variables $s_{vuy} + t_v^{PJ}$ where $u \in \{1,...,U_v\}$ and $y \in \{1,...,Y_v\}$ for strategy $v \in V$. If a turbine is visited, an installation vessel must at least jack-up, install, jack-down and transit back to a port before the time horizon has ended.

Note that the new upper bounds S_v, F_v, and H_v make rather small improvements on the former upper bound P (from Model 1), especially for long time horizons. The new upper bounds cannot be made tighter because the decision on how many cycles a strategy performs, and the decision on how many turbines a strategy installs on each cycle, are both left open.

The new upper bounds contribute to a slightly stronger linear relaxation, which is helpful when running a branch and bound algorithm.

Time tracking is formulated similarly to Model 1 in Section 3.3.2:

$$e_{v(u-1)} + \sum_{y=1}^{Y_v} t_v^L \theta_{vuy} \le q_{vu}, \ \forall \ v \in V, \ u \in \{1, ..., U_v\} \tag{4.4.1}$$

$$q_{vu} + \sum_{k \in K} t_{kv}^K x_{kvu} \le s_{vu1}, \ \forall \ v \in V, \ u \in \{1, ..., U_v\} \tag{4.4.2}$$

$$s_{vuy} + t_v^{PJ} - S_v(1 - \theta_{vuy}) \le f_{vuy}, \ \forall \ v \in V, \ u \in \{1, ..., U_v\}, \ y \in \{1, ..., Y_v\} \tag{4.4.3}$$

$$f_{vuy} + t_v^I - F_v(1 - \theta_{vuy}) \le g_{vuy}, \ \forall \ v \in V, \ u \in \{1, ..., U_v\}, \ y \in \{1, ..., Y_v\} \tag{4.4.4}$$

$$g_{vuy} + t_v^{PJ} - H_v(1 - \theta_{vuy}) \le h_{vuy}, \ \forall \ v \in V, \ u \in \{1, ..., U_v\}, \ y \in \{1, ..., Y_v\} \tag{4.4.5}$$

$$h_{vu(y-1)} + t_v^T - H_v(1 - \theta_{vuy}) \le s_{vuy}, \ \forall \ v \in V, \ u \in \{1, ..., U_v\}, \ y \in \{2, ..., Y_v\} \tag{4.4.6}$$

$$h_{vuy} + \sum_{k \in K} t_{kv}^T x_{kvu} \le e_{vu}, \ \forall \ v \in V, \ u \in \{1, ..., U_v\}, \ y \in \{1, ..., Y_v\} \tag{4.4.7}$$

$$e_{vu} \le P, \quad \forall \ v \in V, \ u \in \{0, ..., U_v\} \tag{4.4.8}$$

$$e_{vu} - e_{v0} \le E_v, \quad \forall \ v \in V, \ u \in \{1, ..., U_v\} \tag{4.4.9}$$

Constraints (4.4.1) and (4.4.2) consider loading and port transit to wind farm.

Constraints (4.4.3)-(4.4.5) consider jack-up, installation and jack-down at each turbine visited during a cycle. Note the integration of the new upper bounds S_v, F_v, and H_v.

Constraints (4.4.6) consider transit in between turbines, and these are only constraining if $y \in \{2, ..., Y_v\}$ or more turbines are installed with strategy $v \in V$ on cycle $u \in \{1, ..., U_v\}$ ($\theta_{vuy} = 1$).

Constraints (4.4.7) consider transit from wind farm back to port and the end of cycle $u \in \{1, ..., U_v\}$ with strategy $v \in V$.

Constraints (4.4.8) and (4.4.9) are unchanged from (3.3.13) and (3.3.14) in Model 1.

4.5 REDEFINING WEATHER WINDOWS

4.5.1 *Redefining weather window parameters*

Weather windows are still considered for transit, positioning and installation:

W_v^T: Number of weather windows for transiting with strategy $v \in V$
W_v^{PJ}: Number of weather windows for positioning with strategy $v \in V$
W_v^I: Number of weather windows for installing a turbine with strategy $v \in V$
a_{vn}^I: Start of weather window $n \in \{1, ..., W_v^I\}$ for installing with strategy $v \in V$
b_{vn}^I: End of weather window $n \in \{1, ..., W_v^I\}$ for installing with strategy $v \in V$
a_{vn}^{PJ}: Start of weather window $n \in \{1, ..., W_v^{PJ}\}$ for positioning with strategy $v \in V$
b_{vn}^{PJ}: End of weather window $n \in \{1, ..., W_v^{PJ}\}$ for positioning with strategy $v \in V$
a_{vn}^T: Start of weather window $n \in \{1, ..., W_v^T\}$ for transiting with strategy $v \in V$
b_{vn}^T: End of weather window $n \in \{1, ..., W_v^T\}$ for transiting with strategy $v \in V$

Weather restrictions for installations (W_v^I, a_{vn}^I, b_{vn}^I) are only given for complete turbine installations, and are not considered for each component. Therefore, all weather window parameters are only dependent on vessel strategies.

4.5.2 *Redefining weather window restrictions*

Binary decision variables for weather windows are similar to those of Model 1:

$$N^I_{vuyn} = \begin{cases} 1, & \text{if turbine } y \in \{1,..,Y_v\} \text{ on cycle } u \in \{1,...,U_v\} \text{ is installed with} \\ & \text{strategy } v \in V \text{ in weather window } n \in \{1,...,W^I_v\}, \\ 0, & \text{otherwise} \end{cases}$$

$$N^{PJ1}_{vuyn} = \begin{cases} 1, & \text{if strategy } v \in V \text{ enters position at turbine } y \in \{1,..,Y_v\} \text{ on} \\ & \text{cycle } u \in \{1,...,U_v\} \text{ in weather window } n \in \{1,...,W^{PJ}_v\}, \\ 0, & \text{otherwise} \end{cases}$$

$$N^{PJ2}_{vuyn} = \begin{cases} 1, & \text{if strategy } v \in V \text{ exits position at turbine } y \in \{1,..,Y_v\} \text{ on} \\ & \text{cycle } u \in \{1,...,U_v\} \text{ in weather window } n \in \{1,...,W^{PJ}_v\}, \\ 0, & \text{otherwise} \end{cases}$$

$$N^T_{vuyn} = \begin{cases} 1, & \text{if strategy } v \in V \text{ transits to turbine } y \in \{1,..,Y_v+1\} \text{ on} \\ & \text{cycle } u \in \{1,...,U_v\} \text{ in weather window } n \in \{1,...,W^T_v\}, \\ 0, & \text{otherwise} \end{cases}$$

Note that all the binary variables above have four indices, where some variables in Model 1 had up to five indices (see Section 3.4.2).

The variables N^T_{vuyn} are defined for all transits to turbine $y \in \{1,...,Y_v+1\}$. The extra instance of Y_v+1 must be added for the transit back to port to be considered (if the maximum amount of turbines is loaded).

All transits are weather restricted:

$$\sum_{n=1}^{W^T_v} N^T_{vu1n} = \theta_{vu1}, \qquad \forall\ v \in V,\ u \in \{1,...,U_v\} \tag{4.5.1}$$

$$\sum_{n=1}^{W^T_v} N^T_{vu(y+1)n} = \theta_{vuy}, \qquad \forall\ v \in V,\ u \in \{1,...,U_v\},\ y \in \{1,...,Y_v\} \tag{4.5.2}$$

Constraints (4.5.1) and (4.5.2) make sure all assigned transits happen within one weather window. Note that N^T_{vuyn} considers transit *to* turbine $y \in \{1,...,Y_v\}$ (or transit to port).

All transits must be made within assigned time intervals:

$$\sum_{n=1}^{W^T_v} N^T_{vu1n} a^T_{vn} \le q_{vu}, \qquad \forall\ v \in V,\ u \in \{1,...,U_v\} \tag{4.5.3}$$

$$q_{vu} + \sum_{k \in K} t^K_{kv} x_{kvu} - S_v(1-\theta_{vu1}) \le \sum_{n=1}^{W^T_v} N^T_{vu1n} b^T_{vn}, \qquad \forall\ v \in V,\ u \in \{1,...,U_v\} \tag{4.5.4}$$

Constraints (4.5.3) and (4.5.4) make sure the first transit with strategy $v \in V$ from port to wind farm is within a weather window.

Transits in between turbines are also restricted by weather:

$$\sum_{n=1}^{W_v^T} N_{vu(y+1)n}^T a_{vn}^T \leq h_{vuy}, \qquad \forall\, v \in V,\ u \in \{1,\dots,U_v\}\ y \in \{1,\dots,Y_v\} \tag{4.5.5}$$

$$h_{vu(y-1)} + t_v^T - H_v(1-\theta_{vuy}) \leq \sum_{n=1}^{W_v^T} N_{vuyn}^T b_{vn}^T, \qquad \forall\, v \in V,\ u \in \{1,\dots,U_v\},\ y \in \{2,\dots,Y_v\} \tag{4.5.6}$$

Constraints (4.5.5) and (4.5.6) make sure the transits in between turbines are made within a weather window.

Note that constraints (4.5.5) also make sure any transit from turbine $y \in \{1,\dots,Y_v\}$ is done after a weather window has started.

If strategy $v \in V$ does not load and install the maximum amount of turbines on cycle $u \in \{1,\dots,U_v\}$, but instead installs $y^* < Y_v$ turbines, the transit to turbine y^*+1 is in fact a transit back to port:

$$h_{vuy} + \sum_{k\in K} t_{kv}^K x_{kvu} - H_v(1-\theta_{vuy}+\theta_{vu(y+1)}) \leq \sum_{n=1}^{W_v^T} N_{vu(y+1)n}^T b_{vn}^T, \qquad \forall\, v \in V,\ u \in \{1,\dots,U_v\},\ y \in \{1,\dots,Y_v-1\} \tag{4.5.7}$$

Constraints (4.5.7) and (4.5.5) make sure the port transit from the final turbine installed with strategy $v \in V$ on cycle $u \in \{1,\dots,U_v\}$ is done within a weather window.

Note that constraints (4.5.7) are only constraining for strategy $v \in V$ on cycle $u \in \{1,\dots,U_v\}$ if $\theta_{vuy^*} = 1$ and $\theta_{vu(y^*+1)} = 0$ for some $y^* < Y_v$.

If the maximum amount of turbines are installed on a cycle, the last transit is restricted by weather:

$$h_{vuY_v} + \sum_{k\in K} t_{kv}^K x_{kvu} - H_v(1-\theta_{vuY_v}) \leq \sum_{n=1}^{W_v^T} N_{vu(Y_v+1)n}^T b_{vn}^T, \qquad \forall\, v \in V,\ u \in \{1,\dots,U_v\} \tag{4.5.8}$$

Constraints (4.5.8) and (4.5.5) make sure the transit back to port with strategy $v \in V$ happens within a weather window if Y_v turbines are installed.

Constraints are redefined for entering installation position:

$$\sum_{n=1}^{W_v^{PJ}} N_{vuyn}^{PJ1} a_{vn}^{PJ} \leq s_{vuy}, \quad \forall\, v \in V,\ u \in \{1,\dots,U_v\},\ y \in \{1,\dots,Y_v\} \tag{4.5.9}$$

$$s_{vuy} + t_v^{PJ} - S_v(1-\theta_{vuy}) \leq \sum_{n=1}^{W_v^{PJ}} N_{vuyn}^{PJ1} b_{vn}^{PJ}, \quad \forall\, v \in V,\ u \in \{1,\dots,U_v\},\ y \in \{1,\dots,Y_v\} \tag{4.5.10}$$

$$\sum_{n=1}^{W_v^{PJ}} N_{vuyn}^{PJ1} = \theta_{vuy}, \quad \forall\, v \in V,\ u \in \{1,\dots,U_v\},\ y \in \{1,\dots,Y_v\} \tag{4.5.11}$$

Constraints (4.5.9)-(4.5.11) make sure jack-up happens within a given weather window for each turbine.

Similarly, constraints are also redefined for exiting installation position:

$$\sum_{n=1}^{W_v^{PJ}} N_{vuyn}^{PJ2} a_{vn}^{PJ} \leq g_{vuy}, \quad \forall\ v \in V,\ u \in \{1,\ldots,U_v\},\ y \in \{1,\ldots,Y_v\} \tag{4.5.12}$$

$$g_{vuy} + t_v^{PJ} - H_v(1-\theta_{vuy}) \leq \sum_{n=1}^{W_v^{PJ}} N_{vuyn}^{PJ2} b_{vn}^{PJ}, \quad \forall\ v \in V,\ u \in \{1,\ldots,U_v\},\ y \in \{1,\ldots,Y_v\} \tag{4.5.13}$$

$$\sum_{n=1}^{W_v^{PJ}} N_{vuyn}^{PJ2} = \theta_{vuy}, \quad \forall\ v \in V,\ u \in \{1,\ldots,U_v\},\ y \in \{1,\ldots,Y_v\} \tag{4.5.14}$$

Constraints (4.5.12)-(4.5.14) make sure jack-down happens within a given weather window for each turbine.

Note that any jack-up and jack-down with strategy $v \in V$ must take place within one weather window through (4.5.11) and (4.5.14).

Weather window constraints for installations now apply to each wind turbine:

$$\sum_{n=1}^{W_v^{PJ}} N_{vuyn}^{I} a_{vn}^{PJ} \leq f_{vuy}, \quad \forall\ v \in V,\ u \in \{1,\ldots,U_v\},\ y \in \{1,\ldots,Y_v\} \tag{4.5.15}$$

$$f_{vuy} + t_v^{I} - F_v(1-\theta_{vuy}) \leq \sum_{n=1}^{W_v^{PJ}} N_{vuyn}^{I} b_{vn}^{PJ}, \quad \forall\ v \in V,\ u \in \{1,\ldots,U_v\},\ y \in \{1,\ldots,Y_v\} \tag{4.5.16}$$

$$\sum_{n=1}^{W_v^{PJ}} N_{vuyn}^{I} = \theta_{vuy}, \quad \forall\ v \in V,\ u \in \{1,\ldots,U_v\},\ y \in \{1,\ldots,Y_v\} \tag{4.5.17}$$

Constraints (4.5.15)-(4.5.17) make sure installation of each complete turbine is performed within a weather window.

The next section presents the simplified objective function in Model 2.

4.6 REDEFINING THE OBJECTIVE FUNCTION

Some vessel and port costs are unchanged in the simplified model compared to Model 1 (see Section 3.5):

c_k^K: Fixed cost operating from port $k \in K$

c_v^{TC}: Time charter cost per time unit for vessel strategy $v \in V$

c_v^M: Mobilization cost for starting chartering of vessel strategy $v \in V$

Operational vessel costs are based on fuel consumption and fuel price in Model 1 (see Section 3.5). Inspired by current oil prices, marine fuel price can be assumed to be around \$ 350 /ton (Ship & Bunker, 2017).

Dalgic et al. (2015) suggest fuel consumption for a jack-up to range in between 2 tons/day when staying at the port and 10 tons/day when in operation. This gives a price range of \$ 30-145 /hour for self-propelled jack-up vessels. Tugs are assumed to use 5 tons/day per barge which gives a price of about \$ 70 /hour.

Compared to a daily charter rate of \$ 150,000, fuel costs make up about 1-2 % of the total costs during a day. In the context of optimization, considering fuel consumption may therefore not be crucial in terms of finding an optimal strategy. In Model 2, fuel costs are omitted.

The redefined objective function identifies port costs and vessel mobilization- and charter costs:

$$\min \sum_{k \in K} c_k^K \delta_k + \sum_{v \in V} \left(c_v^M \gamma_v + c_v^{TC} E_v \right) \tag{4.6.1}$$

The terms in (4.6.1) identifies the same costs as the objective function (3.5.1) formulated in Chapter 3 without considering fuel consumption.

4.7 SUMMARY

A complete mathematical formulation of the simplified model presented in Chapter 4 can be found in Appendix B.

Simple tests of Model 2 show promising results in acquiring feasible and/or optimal solutions. Model 2 is used to further analyse realistic scenarios. The next chapter presents implementation and analyses with Model 2.

5

EXPERIMENTS

The following chapter presents some numerical experiments with Model 2 (see Chapter 4).

The purpose of these experiments are mainly to:

1. Test how large problem instances Model 2 can tackle.
2. Analyse how numerical results may support strategic installation decisions.
3. Investigate how solution outputs differ with changes in uncertain parameters.

The input data for the numerical experiments are mainly inspired by the work of Emre Uraz in his Master's thesis (Uraz, 2011) and an evaluation made for a Korean wind farm (Ahn et al., 2016) presenting technical and historic data for offshore vessels and offshore wind farms.

Model 2 is implemented in AMPL, and different instances are run with the CPLEX solver.

5.1 GATHERING DATA

All data inputs are inspired by realistic data. However, an optimal solution is sought based on simplified and deterministic assumptions about operation durations, costs and weather realizations. Therefore, using Model 2 to propose an exact project schedule or an accurate project cost estimation has limited value.

For the purpose of strategic decision support concerning ports and vessel fleet, Model 2 is more relevant.

5.1.1 *Fixed port cost*

Real cost data are difficult to come across due to industry confidentiality and continuously changing markets.

Estimating actual fixed port costs is especially challenging, because there are several costs related to ports beyond the framework considered in the current work.

A report from the LEANWIND project (Akbari, 2015) states physical characteristics (like lifting capability and space for component handling) to be the most important factors when picking suitable installation ports.

Fixed port costs are assumed to be in the order of $ 1,000,000.

5.1.2 *Distances*

Costs related to operating from a port depend on the distance from the port to the wind farm.

According to a test case in a LEANWIND report, distance from wind farm to potential ports range from 50 to 270 km (Akbari, 2015).

Distances in between neighboring turbines are usually dependent on turbine size, and tend to be about 6 times the rotor diameter (Uraz, 2011). The rotor diameters of offshore wind turbines can grow as large as 180 m (Adwen's AD 8-180 wind turbine model).

We consider neighbouring turbines to be located 1 km apart to somehow account for the varying distances in between turbines.

5.1.3 *Vessel efficiency*

The model assumes all vessels move with constant speed independent of load carried or weather conditions. The installation vessels available in the market today vary in operational speed. Technical vessel data suggest a speed range in between 10-13 knots (Uraz, 2011) for self-propelled installation vessels.

Large barges with high transportation capacity need to be towed, and they tend to move more slowly than self-propelled installation vessels. All barges are assumed to transit with a speed of 4 knots (Ahn et al., 2016).

Jack-up speed varies from 0.5 to 2.0 m/min (Uraz, 2011). Jack-up barges tend to jack up more slowly than self-propelled jack-ups. The operational air gap, i.e. the height above sea level when fully jacked up, also varies for different vessels in between 10-20 m. Assuming an average depth of 30 m and a sea bed penetration of 5 m, the duration of each jacking operation ranges in between 0.5 and 3 hours.

5.1.4 *Loading and assembly strategy*

The current experiments consider installation of top-structures. All vessel strategies are assumed to load complete sets of top-structures, and each offshore lift is assumed to take 3 hours for all components except blades. Offshore blade lifts are assumed to take 2 hours. Any loading lift is assumed to take 2 hours.

As mentioned in Section 2.2.4, top-structures can be partly assembled to reduce the amount of lifts per turbine. However, partly assembled components require heavier lifts and calmer weather.

Two component assembly strategies are recommended options by Uraz (2011). The first option is to assemble only the tower onshore and keep the other components separate. This option requires 5 loading and offshore lifts with less strict weather restrictions. The option of keeping the components separate ensures more turbines can be loaded on each cycle.

The second option is to assemble the nacelle, hub and two blades together in a so called "bunny-ear" configuration (Uraz, 2011). The tower is also assembled, and the last blade is kept separate. This option requires only 3 lifts. However, the weather restrictions are stricter for this strategy, due to the aerodynamic forces acting on the partly assembled rotor. In addition, fewer turbines can be transported on each cycle, and heavier components require more crane capacity.

5.1.5 *Vessel costs*

Vessel mobilisation and charter costs can vary greatly with season and demand, and these inputs therefore contribute to uncertainty when modeling the current problem.

According to Ahn et al. (2016), the time charter day rate is assumed to range in between:

- $ 150,000 - 250,000 for self-propelled jack-up vessels,
- $ 100,000 - 180,000 for jack-up barges,
- $ 30,000 - 50,000 for cargo barges,
- $ 1,000 - 5,000 for tug boats.

The mobilization cost of a vessel depends on the charter rate, and the position of a vessel before the charter begins. Some estimates of such costs have been made by Kaiser & Snyder (2010), and these estimates range widely in between $ 100,000 - 1,000,000. We assume in the current experiments that mobilization costs are 5 times the charter day rate for a vessel strategy.

5.1.6 *Time horizon and weather window input*

Each working day is considered to be 12 hours. Time parameters and variables are measured in the unit of working days, e.g. jacking operations range in between 0.5 and 3 hours which is scaled to 0.042 and 0.25 working days. The resolution of weather data is one working day, i.e. vessel strategy $v \in V$ either can or cannot perform a given operation during one entire working day due to weather restrictions.

Historical wind speed and significant wave height data for an offshore site from year 2000-2010 are supplied by Metno (NORCOWE, 2017) from the NORA10 reanalysis with a 10 km horizontal resolution through the NORCOWE referance wind farm. Weather data are defined every 3 hours, and

Operation	Wind speed (m/s)	Significant wave height (m)
Transit	20-25	1.5-3.0
Setup	15-20	1.5-2.5
Installation	7-15	3.0-6.0

Table 5.1.1.: Weather restriction ranges for vessel operations

Port	Fixed cost c_k^K [$]	Distance to farm [km]
Port 1	1,000,000	250
Port 2	2,000,000	150
Port 3	3,000,000	50

Table 5.2.1.: Port data input

we consider the worst weather condition from 6 a.m. to 6 p.m. to define the weather condition for each working day.

Inspired by technical vessel data (Uraz, 2011), weather limitations are assumed to range in between values presented in Table 5.1.1. Historical data are analysed to produce weather windows for the vessel strategies considering the operational restrictions. Weather windows for the operation of consideration are produced as time intervals when both wind speed and significant wave height are below the given limit.

5.2 DEFINING PORTS AND VESSEL STRATEGIES

5.2.1 *Wind farm and ports*

We define three different options for installation ports:

- Manufacturing port located far away from wind farm with low fixed cost (Port 1).
- Assembly port located closer to wind farm with medium cost (Port 2).
- Assembly port located close to wind farm with high fixed cost (Port 3).

Data input for ports can be found in Table 5.2.1. Further, we define three different vessel strategies inspired by realistic options.

5.2.2 *Vessel strategy: Feed*

The first strategy is referred to as the "feed" strategy (see Table 5.2.2). One cargo barge carrying up to 10 turbines in 5 parts on each trip travels in between port and wind farm feeding a jack-up barge with turbine components.

Strategy	Feed	Bunny transit	Unmounted transit
Charter rate [$/day]	144,000	200,000	180,000
Mobilization cost [$]	720,000	1,000,000	900,000
Time, load [day]	0.83	0.5	0.83
Time, setup [day]	0.125	0.083	0.083
Time, install [day]	1.00	0.67	1.00
Time, turbine transit [day]	0.011	0.004	0.004
Turbines per cycle [pcs]	10	4	8
Wind restriction, transit [m/s]	20	15	20
Wind restriction, setup [m/s]	20	15	20
Wind restriction, install [m/s]	10	8	12
Wave restriction, transit [m]	1.5	3.0	3.0
Wave restriction, setup [m]	1.5	2.0	2.0
Wave restriction, install [m]	5.0	5.0	5.0

Table 5.2.2.: Data for the considered strategies

We assume two tugs are used with a charter rate of $ 4,000 /day to mobilize the barges. The total charter rate for both barges is assumed to be $ 140,000 /day. The mobilization cost is assumed to be 5 times the charter rate, that is $ 720,000.

All transits are assumed to happen at 4 knots. Some time is cut from the transit in between wind farm and port due to an assumed overlap of positioning and port transit (see Section 5.2.5). Jack-up/jack-down is assumed to take 1.5 hours.

The feed strategy is vulnerable to wave conditions (Ahn et al., 2016).

5.2.3 *Vessel strategy: Bunny transit*

The second strategy is referred to as the "bunny transit" strategy (see Table 5.2.2). One self-propelled installation vessel carrying up to 4 turbines on each trip transports and installs each turbine. The turbine is loaded and installed in 3 parts in a "bunny-ear" configuration (see Section 5.1.4).

We assume the charter rate is $ 200,000 /day, so the mobilization cost is assumed to be $ 1,000,000. The transit speed is assumed to be 10 knots, and jack-up/jack-down is assumed to take 1 hour.

The "bunny transit" strategy is sensitive to installation lifts and transits due to wind forces acting on the partly assembled rotor.

5.2.4 *Vessel strategy: Unmounted transit*

The third strategy is referred to as the "unmounted transit" strategy (see Table 5.2.2). This strategy is similar to the "bunny transit" strategy, except that each turbine is loaded and installed in 5 parts with only the tower assembled (see Section 5.1.4). We assume therefore up to 8 turbines can be transported during each cycle.

Transit time t^K_{kv}	Port 1	Port 2	Port 3
Feed [day]	2.67	1.58	0.42
Bunny transit [day]	1.08	0.67	0.25
Unmounted transit [day]	1.08	0.67	0.25

Table 5.2.3.: Transit time in between different ports and wind farm with different strategies

Charter rate is assumed lower than the "bunny transit" strategy since each lift requires less crane capacity, and therefore there are less requirements for the installation vessel.

Other vessel data are assumed to be the same as for the "bunny transit" strategy, but the wind restrictions are less strict.

5.2.5 *Port transit time*

With the vessel speed for strategy $v \in V$ and port to farm distance for port $k \in K$, transit time from port to wind farm can be calculated (see Table 5.2.3).

Note that 1.5 hours of transit time with the "feed" strategy has been cut, since the transit with the cargo barge is assumed to start when jack-down of the installation barge starts.

5.3 NUMERICAL EXPERIMENTS AND RESULTS

With three strategies and three ports, the size of our test case further depends on the number R of turbines and the total length P of the time horizon.

In the next sections, optimal solutions are sought for different instances.

5.3.1 *Experiment 1: 20 turbines and 1 month*

We first consider a wind farm with 20 wind turbines and a 1 month time horizon (Experiment 1).

Upon solving the problem without any weather restrictions, the "bunny transit" strategy proves to be the optimal strategy. This makes sense because the "bunny transit" strategy is the most time effective strategy (see Table 5.2.2). The solution changes if the charter rate for the "bunny transit" strategy is sufficiently high compared to the less time effective strategies.

When including weather restrictions, we choose to consider historical weather data from May 2000 (NORCOWE, 2017). The CPLEX solver finds the optimal solution for Experiment 1 in 71.3 seconds with a total cost of $ 11,106,600 (see Solution 1.1 in Table 5.3.1). The optimal vessel choice is a combination of the "bunny transit" and the "feed" strategy operating from Port 3.

Experiment 1

Without duplication (Solution 1.1)
Objective: $ 11,106,600

Strategy [$\in V$]	Cycles [pcs]	Turbines [pcs]	Charter [day]
Feed	1	6	14.375
Bunny transit	5	14	22.583
Unmounted transit	0	0	0

With duplication (Solution 1.2)
Objective: $ 10,958,000

Strategy [$\in V$]	Cycles [pcs]	Turbines [pcs]	Charter [day]
Feed 1&2	0	0	0
Bunny transit 1	3	10	14.9
Bunny transit 2	3	10	14.9
Unmounted transit 1&2	0	0	0

Table 5.3.1.: Optimal strategies for 20 turbines with 1 month time horizon.

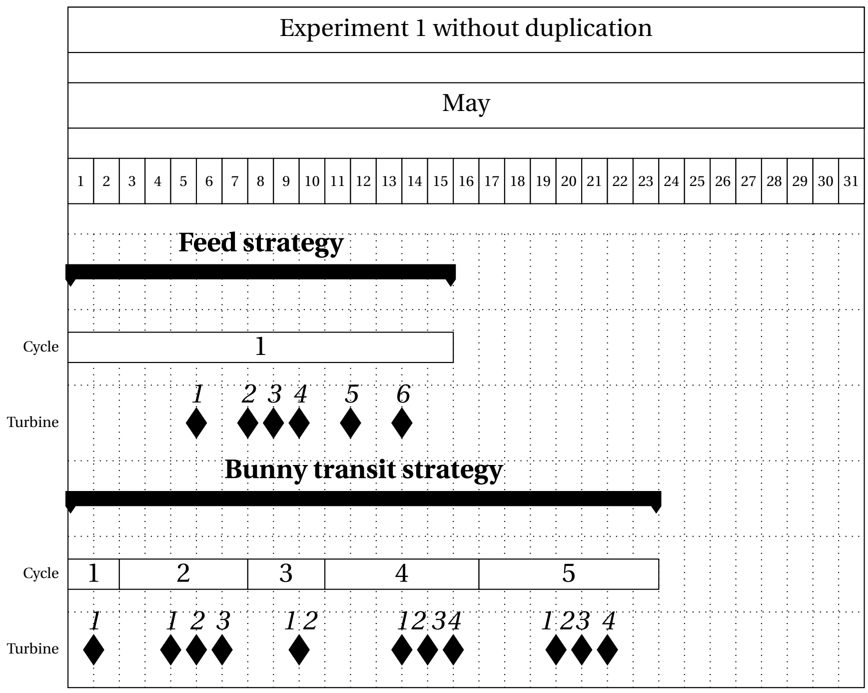

Figure 5.3.1.: Gantt chart presenting optimal installation schedule (Solution 1.1) for Experiment 1.

The timing for turbine installations is presented in a Gantt chart (see Figure 5.3.1). The top of the chart represents time, and the duration of each vessel charter period is represented by the black lines. The white boxes with numbers represent cycle durations, and the black milestones along with the numbers above represent the start of installation of turbines on a given cycle.

If we allow strategies to be duplicated (see Section 4.2.2), the optimal solution is found after 2,528 seconds and total costs are reduced to $ 10,958,000. The "feed" strategy is no longer optimal, and the "bunny transit" strategy is duplicated still operating from Port 3 (see Solution 1.2 in Table 5.3.1). All vessel operations in the duplicated solution happens within the same weather windows.

If we shorten all weather windows for installation operations for the "bunny transit" strategy by one working day, the optimal solution is found after 2,593 seconds and the total costs measure $ 11,555,200. The "unmounted transit" strategy is duplicated with a total project cost increase of 5.4 % from Solution 1.2 (see Table 5.3.1). In this case, it proves optimal to operate from Port 1.

If we decrease the charter rate of the "unmounted transit" strategy to $ 160,000 /day (−11 %) and the mobilisation cost to $ 800,000, the optimal solution is found after 1,883 seconds and total costs are reduced by 5.2 % from Solution 1.2 (see Table 5.3.1). The "unmounted transit" strategy is duplicated with the same schedule as above operating from Port 1.

5.3.2 *Experiment 2: 40 turbines and 3 months*

In the next experiment (Experiment 2), we consider 40 turbines that are to be installed within 3 months. Weather data is selected from May to July 2000 (NORCOWE, 2017).

The CPLEX solver has a harder time proving an optimal solution compared to Experiment 1, although a feasible solution is obtained within seconds. After running iterations for 10,000 seconds, an optimal solution is not proven.

An optimality gap of 40.1 % is obtained with a combination of the "bunny transit" strategy and the "unmounted transit" strategy operating from Port 3, and the objective cost measures $ 19,270,013 (see Solution 2.1 in Table 5.3.2 and Figure 5.3.2). The best feasible solution is obtained after 9,000 seconds.

With the possibility of duplicated strategies, the optimality gap reaches 43.8 % after 10,000 seconds, and the total costs sum up to $ 19,470,640 (see Solution 2.2 in Table 5.3.2). The best feasible solution is obtained after 6,000 seconds, and it does not include strategy duplication. The strategy choices are the same as for the experiment without duplication possibilities, namely a combination of the "bunny transit" and the "unmounted transit" strategy.

Experiment 2
Runtime: 10,000 seconds

Without duplication (Solution 2.1)
Objective: $ 19,270,013
Optimality gap: 40.1 %

Strategy [$\in V$]	Cycles [pcs]	Turbines [pcs]	Charter [day]
Feed	0	0	0
Bunny transit	5	14	21.583
Unmounted transit	5	26	55.558

With duplication (Solution 2.2)
Objective: $ 19,470,640
Optimality gap: 43.8 %

Strategy [$\in V$]	Cycles [pcs]	Turbines [pcs]	Charter [day]
Feed	0	0	0
Bunny transit	2	8	11.718
Unmounted transit	5	32	67.928

Table 5.3.2.: Best solution obtained for 40 turbines with 3 months time horizon after 10,000 seconds computer time.

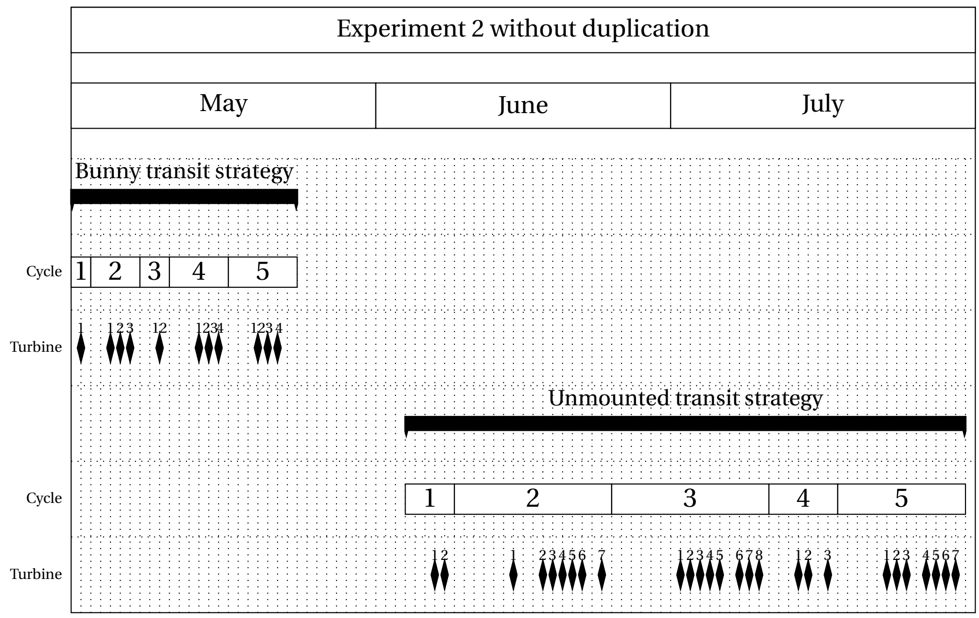

Figure 5.3.2.: Gantt chart presenting the best installation schedule (Solution 2.1) for Experiment 2.

The solution obtained with the possibility of strategy duplication (Solution 2.1) produces higher costs than the solution obtained without the possibility of duplication (Solution 2.2). Solution 2.1 is feasible in the instance allowing strategy duplication, but it is not obtained within the same time span. This is likely due to the fact that the problem instance grows significantly with 6 strategy choices instead of only 3.

Experiment 2 demonstrate that including more possibilities does not necessarily produce better solutions, and that our ability to draw conclusions from solutions obtained without reaching optimality is limited.

Since the "feed" strategy is not mobilized in Experiment 2, we try to simplify the instance by eliminating the "feed" strategy entirely ($\gamma_{\text{feed}} = 0$). With no possibility of duplication, no improvement in the objective is found after 4,000 seconds.

5.3.3 *Experiment 3: 100 turbines and 5 months*

We expand our case again to 100 turbines and 5 months time horizon (Experiment 3). Weather data is based on historical data from May to September 2000 (NORCOWE, 2017). No optimal solution is proven within a time frame of 20,000 seconds with the CPLEX solver. A feasible solution is obtained within minutes.

After 20,000 seconds, an optimality gap of 70.3 % is realized, and the total costs measure $ 43,086,208. The best feasible solution is obtained in the very last iterations. In this solution, all strategies are mobilized operating from Port 3. The "unmounted transit" strategy is chartered longest and assigned most turbine installations (see Solution 3.1 in Table 5.3.3). Note that the sum of the charter periods exceed the total time horizon (154 working days), which calls for the option of strategy duplication to be investigated.

To keep the problem instance as small as possible, we consider duplication of the "unmounted transit" strategy as the only strategy possibility ($\gamma_{\text{feed}} = \gamma_{\text{b.transit}} = 0$).

After 5,000 seconds, the total costs drop below the previous instance without strategy duplication, and an objective of $ 42,407,660 is obtained with duplication of the "unmounted transit" strategy operating from Port 3 (see Solution 3.2 in Table 5.3.3). Note that the operation assignments differ for the duplicated strategy. The solution remains unchanged after running the algorithm for 20,000 seconds.

Experiment 3
Runtime: 20,000 seconds

Without duplication (Solution 3.1)
Objective: $ 43,086,0208
Optimality gap: 70.3 %

Strategy [$\in V$]	Cycles [pcs]	Turbines [pcs]	Charter [day]
Feed	2	18	45.552
Bunny transit	8	23	42.260
Unmounted transit	9	59	130.328

With duplication (Solution 3.2)
Objective: $ 42,407,660

Strategy [$\in V$]	Cycles [pcs]	Turbines [pcs]	Charter [day]
Unmounted transit 1	10	55	117.836
Unmounted transit 2	8	45	96.651

Table 5.3.3.: Best solution obtained for 100 turbines with 5 months time horizon after 20,000 seconds computer time.

5.4 DISCUSSION

5.4.1 *Computational capability*

The experiments in Chapter 5 demonstrate the muscle power of the simplified Model 2 presented in Chapter 4. All numerical experiments provide feasible solutions, but solutions for larger and more relevant cases (see Section 5.3.2 and 5.3.3) are not proven optimal. This is due to one of the following reasons:

- (1) the feasible solution is far from optimality,
- (2) the linear relaxations provide poor lower bounds, or
- (3) a combination of both.

The instance of Experiment 1 (see Section 5.3.1) seems to be close to the largest realistic instance where the CPLEX solver can prove optimality within a reasonable time frame.

5.4.2 *Model credibility*

As mentioned in Section 5.1, the data inputs are static, and the model does not consider uncertainty explicitly in each case. The trait of not dealing with uncertainty explicitly is demonstrated to be unfortunate through Experiment 1 (see Section 5.3.1). With a small change in uncertain parameters concerning weather and costs, the solution output is altered completely in terms of both port and vessel strategy decisions. Any conclusions drawn to aid strategic decisions are thus rather speculative.

5.4.3 *Interpretation of vessel strategy decisions*

The results from Experiment 1, 2 and 3 indicate that the vessel mix tend to change with growing wind farm sizes. For small farms (Experiment 1), a time effective strategy like the "bunny transit" strategy seems to be a good choice, despite the fact that the "bunny transit" strategy is sensitive to wind conditions during installation lifts. For larger farms (Experiment 2 and 3), weather delays become more relevant, and the "unmounted transit" strategy, allowing installation in higher winds, seems to be favorable.

When the "feed" strategy is mobilized in the numerical experiments, it is in addition to other strategies. Due to high wave sensitivity during rather slow transportation, barges are subject to severe delays compared to self-propelled vessels, and thus the "feed" strategy is unfavorable as the only vessel strategy.

It is worth noting that most cycles in all experiments are performed without fully loading vessels to their capacity. The seemingly nice benefit of being able to carry many wind turbines per trip seem to be of small significance. This may be a consequence of the weather sensitive installation lifts being the bottlenecks of the process, as concluded by Barlow et al. (2015). After a weather window for installation has ended, a vessel is usually better off returning to a port to reload components rather than waiting for a new weather window. Since loading operations are not considered to be dependent on weather conditions in Model 2, spending less time on loading may be a good way of utilizing weather windows.

5.4.4 *Interpretation of port decisions*

As mentioned in Section 5.1.1, fixed port costs are especially hard to estimate within the framework of the current problem. The model may point out the cost reduction needed to defend the use of a port located far away from the wind farm. Nevertheless, the cost estimate related to the use of a port is dependent on the vessel charter rates. As the farm size grows, the number of port transits must increase, and the travel time from port to farm becomes more critical in terms of fitting weather windows and simultaneously minimizing vessel charter costs. The port decision for larger farms is therefore dependent on how or whether port handling costs increase with increasing number of wind turbines. Experiments 2 and 3 (see Section 5.3.2 and 5.3.3) have not taken such a potential cost increase into account.

The suggested port choice for most numerical experiments in the current chapter is Port 3 with highest fixed costs and shortest travel distance to wind farm (see Table 5.2.3).

Removing the option of operating from Port 3 ($\delta_{\text{Port 3}} = 0$) in Experiment 1, with the possibility of strategy duplication, leads to a total project cost increase of only 0.07 %. In this case, it is optimal to operate from Port 2 with duplication of the "bunny transit" strategy.

The port decision changes from Port 3 to Port 1 in Experiment 1 for cases where the "unmounted transit" strategy is proven the optimal strategy (see Section 5.3.1). This is probably due to longer weather windows for the "unmounted transit" strategy for installation operations, which makes longer transits and lower port handling costs a preferable choice. Note that the choice of Port 1 is based on the poor assumption that there is no uncertainty in the weather forecast.

6

CONCLUSIONS

Operational analyses of offshore logistics related to transportation and installation of offshore wind turbines have been performed in this thesis project. Two mixed integer linear programming models have been developed motivated by the possibility of aiding strategic port and vessel decisions to minimize logistical costs.

6.1 COMPARISON OF MODELS

Model 1, presented in Chapter 3, is a detailed formulation of the problem, in the sense that it leaves many decisions on how to perform installation open. Model 1 has the potential to provide interesting suggestions and solutions, but testing demonstrates that the computational challenge of Model 1 with an exact solver becomes an obstacle when considering any relevant wind farm size.

Model 2 presented in Chapter 4 has fewer decisions left open compared to Model 1, and therefore relevant and realistic instances may be analysed in Chapter 5 through an exact solver (CPLEX). However, Model 2 is based on more assumptions than Model 1, and several decisions are therefore left unconsidered in Model 2.

Developing alternatives to exact methods might make further analysis of both models possible. The benefits of applying a more detailed model, like Model 1, may be significant for the problem considered in the current work; the possibility of finding alternative and clever ways of executing offshore installations is more present with less underlying assumptions.

The routing aspect of Model 1, which contributes significantly to its computational difficulty, is highly simplified in Model 2. Turbine routing may be a crucial consideration for certain wind farms. The fundamental assumption in Model 2, where the distance from port to wind farm is fixed, may essentially be wrong for wind farms spanning large offshore distances.

Components are considered differently in the two models. Model 1 allows vessels to cooperate with installation of predefined component types, whereas Model 2 allows different onshore assembly of components without considering cooperation across vessel strategies.

6.2 DETERMINISTIC ANALYSIS

Both models developed in Chapter 3 and 4 are based on deterministic parameters, which means the solver iterates through sub-problems where all parameters are fixed. This is a basic weakness of both models; the real logistical problem deal with high uncertainties, especially with respect to weather realizations and cost parameters.

Through implementation and testing of the models, it is however clear that even deterministic models struggle to tackle the current logistical problem. We have seen that Model 1 provides feasible solutions only for very small cases, and that the simplified Model 2 cannot prove optimality for larger test cases.

Therefore, the framework of the problem in this project calls for drastic simplifications if stochastic approaches are to become relevant. Thus, on a strategic and aggregated level, a deterministic approach may be a better alternative to aid the project decisions considered in this work.

6.3 DEALING WITH UNCERTAINTY

The parameters with the highest degree of uncertainty in both models are related to costs and weather windows. Through Experiment 1 (see Section 5.3.1), it is demonstrated that the strategic decisions are rather sensitive to changes in weather and cost parameters.

The solutions obtained can become more credible if uncertainty can be dealt with outside the model, for instance by minimizing uncertainty in the weather forecast.

Another way to deal with uncertainty in the models is to run several deterministic experiments with different inputs (see Experiment 1 in Section 5.3.1). By slightly altering uncertain parameters for smaller cases, some insight into the potential impact of changes in parameters is achieved. The numerical experiments in Chapter 5 demonstrate, for instance, how weather windows during installation seem to be a critical factor affecting optimal port and vessel mix. Running many such numerical experiments may further strengthen the reliability of conclusions on how given factors influence strategic decisions, which in turn may inspire future work.

6.4 STRATEGIC DECISIONS FOR LARGE OFFSHORE WIND FARMS

Optimality for numerical experiments with Model 2 in Chapter 5 is proven for instances up to a certain size. The largest instance where optimality is proven is Experiment 1 with strategy duplication. In this instance, three ports and six vessel strategies (three duplicated strategies) are considered as alternatives to install 20 turbines over a 1 month time horizon.

Even though the size of Experiment 1 with strategy duplication is considered rather small in terms of present and future offshore wind farm projects, the strategic decisions suggested might be transferable to larger farms. One can imagine 20 turbines being a fraction of a bigger wind farm, and analyse the problem with Model 2 for different sections of the wind farm.

Considering smaller fractions of the wind farm could be a way of strengthening the validity of the questionable assumption in Model 2 about fixed distance between port and wind farm mentioned in Section 6.1.

Whether the strategic choices are altered when considering large wind farms in an aggregated vs fractionated manner, depends on how the different parameters scale for growing instances. For example, fixed port costs may change considerably with growing wind farms as mentioned in Section 5.4.4. Issues related to any fixed cost, also including vessel mobilisation costs, can make it complicated to consider a large wind farm through smaller instances.

6.5 FUTURE WORK

Further work can be done on developing heuristic methods to solve instances of the models developed in the current work. There is a potential for alternative methods to find feasible and good solutions for relevant instances of Model 1. There is also a potential to tackle large data sets and provide stronger solutions for instances of Model 2.

Stochastic analysis may be relevant for detailed investigation of smaller sub-problems on a more tactical level. Stochastic formulations can be motivated by the recognition of critical uncertain parameters obtained from deterministic analyses. An example of such a sub-problem could be a more detailed analysis on optimizing weather window utilization. Stochastic analyses deal with uncertainty explicitly, and therefore might provide more reliable decision aid. Running several stochastic analyses on tactical decisions, considering different vessel strategies in separate instances, can potentially produce reliable vessel data that can be implemented in simplified and aggregated optimization models.

Appendices

A

MATHEMATICAL FORMULATION OF MODEL 1

A.1 SETS

K: Set of ports

V: Set of vessels

V^T: Set of vessels that can transport components, $V^T \subseteq V$

V^I: Set of vessels that can install components, $V^I \subseteq V$

R: Set of turbine locations

$D = \{d_1, ..., d_{|D|}\}$: Set of component types ordered in installation order

A.2 PARAMETERS

c_k^K: Fixed cost of operating from port $k \in K$

c_v^{TC}: Time charter cost per time unit for vessel $v \in V$

c_v^M: Mobilization cost for starting time chartering of vessel $v \in V$

c_v^L: Cost per time unit for loading vessel $v \in V^T \subseteq V$

c_v^I: Cost per time unit for performing installation with vessel $v \in V^I \subseteq V$

c_v^T: Cost per time for unit transiting vessel $v \in V$

c_v^{PJ}: Cost per time unit for positioning vessel $v \in V^I \subseteq V$

t_d^L: Time needed to load component type $d \in D$

t_{ijv}^T: Time to transport vessel $v \in V$ in between port or turbine location $i \in K \cup R$ and port or turbine location $j \in K \cup R$ $(i \neq j)$

t_v^{PJ}: Time to jack-up/jack-down vessel $v \in V^I \subseteq V$

t_{dv}^I: Time to install component type $d \in D$ with vessel $v \in V^I \subseteq V$

t_{dv}^A: Time to assist installation of component type $d \in D$ with vessel $v \in V^T \subseteq V$

z_v: Transportation capacity of vessel $v \in V^T \subseteq V$

w_d: Weight of component type $d \in D$

P: Length of time horizon

U_v: Maximum number of cycles a vessel can perform given the time horizon

A.3 VARIABLES

$$\delta_k = \begin{cases} 1, & \text{if port } k \in K \text{ is in use,} \\ 0, & \text{otherwise} \end{cases}$$

$$\gamma_v = \begin{cases} 1, & \text{if vessel } v \in V \text{ is mobilized,} \\ 0, & \text{otherwise} \end{cases}$$

$$x_{ijvu} = \begin{cases} 1, & \text{if vessel } v \in V \text{ travels from node } i \in K \cup R \text{ to } j \in K \cup R \ (i \neq j) \\ & \text{on cycle } u \in \{1, \dots, U_v\}, \\ 0, & \text{otherwise} \end{cases}$$

$$\theta_{rdvu} = \begin{cases} 1, & \text{if vessel } v \in V^T \subseteq V \text{ is transporting component type } d \in D \\ & \text{to turbine location } r \in R \text{ on cycle } u \in \{1, \dots, U_v\}, \\ 0, & \text{otherwise} \end{cases}$$

$$\eta_{rdvu} = \begin{cases} 1, & \text{if vessel } v \in V^I \subseteq V \text{ is installing component type } d \in D \\ & \text{at turbine location } r \in R \text{ on cycle } u \in \{1, \dots, U_v\}, \\ 0, & \text{otherwise} \end{cases}$$

$$\rho_{rvu} = \begin{cases} 1, & \text{if vessel } v \in V^I \subseteq V \text{ is performing any installation at} \\ & \text{turbine location } r \in R \text{ on cycle } u \in \{1, \dots, U_v\}, \\ 0, & \text{otherwise} \end{cases}$$

$q_{vu} \in \mathbb{R}_+$: Time when vessel $v \in V$ starts cycle $u \in \{1, \dots, U_v\}$

$e_{vu} \in \mathbb{R}_+$: Time when vessel $v \in V$ ends cycle $u \in \{0, \dots, U_v\}$

$s_{rvu} \in \mathbb{R}_+$: Time when vessel $v \in V$ arrives at turbine $r \in R$ on cycle $u \in \{1, \dots, U_v\}$

$g_{rvu} \in \mathbb{R}_+$: Time when vessel $v \in V^I$ starts jacking down at turbine $r \in R$ on cycle $u \in \{1, \dots, U_v\}$

$h_{rvu} \in \mathbb{R}_+$: Time when vessel $v \in V$ leaves turbine $r \in R$ on cycle $u \in \{1, \dots, U_v\}$

$f_{rd} \in \mathbb{R}_+$: Time when installation of component type $d \in D$ starts at turbine location $r \in R$

$E_v \in \mathbb{R}_+$: Total time vessel $v \in V$ is chartered

A.4 OBJECTIVE FUNCTION

$$\min \sum_{k \in K} c_k^F \delta_k + \sum_{v \in V} \left(c_v^{SC} \gamma_v + c_v^{TC} E_v \right) + \sum_{r \in R} \sum_{d \in D} \sum_{u=1}^{U_v} \left(\sum_{v \in V^T} c_v^L t_d^L \theta_{rdvu} + \sum_{v \in V^I} c_v^I t_{vd}^I \eta_{rdvu} \right) +$$
$$\sum_{i \in K \cup R} \sum_{j \in K \cup R:\ i \neq j} \sum_{v \in V} \sum_{u=1}^{U_v} c_v^T t_{ijv}^T x_{ijvu} + \sum_{r \in R} \sum_{v \in V^I} \sum_{u=1}^{U_v} 2 c_v^{PJ} t_v^{PJ} \rho_{rvu}$$

A.5 CONSTRAINTS

$$x_{ijvu} \leq \gamma_v, \quad \forall\, i \in K \cup R, j \in K \cup R\ (i \neq j),\ v \in V,\ u \in \{1,\dots,U_v\} \tag{A.5.1}$$

$$\sum_{r\in R} x_{krvu} \leq \delta_k, \qquad \forall\, k \in K,\ v \in V,\ u \in \{1,\dots,U_v\} \tag{A.5.2}$$

$$\sum_{r\in R} x_{rkvu} \leq \delta_k, \qquad \forall\, k \in K,\ v \in V,\ u \in \{1,\dots,U_v\} \tag{A.5.3}$$

$$x_{ijvu} \leq \sum_{k\in K}\sum_{r\in R} x_{krvu},\ \forall\, i \in R,\ j \in R\ (i \neq j),\ v \in V,\ u \in \{1,\dots,U_v\} \tag{A.5.4}$$

$$\sum_{i\in K\cup R:\ i\neq r} \left(x_{irvu} - x_{rivu}\right) = 0, \qquad \forall\, r \in R,\ v \in V,\ u \in \{1,\dots,U_v\} \tag{A.5.5}$$

$$\sum_{k\in K}\sum_{r\in R} x_{krvu} \leq 1, \qquad \forall\, v \in V,\ u \in \{1,\dots,U_v\} \tag{A.5.6}$$

$$\sum_{r\in R} x_{krvu} \leq \sum_{r\in R} x_{rkv(u-1)}, \qquad \forall\, k \in K,\ v \in V,\ u \in \{2,\dots,U_v\} \tag{A.5.7}$$

$$\sum_{v\in V^T}\sum_{u=1}^{U_v} \theta_{rdvu} = 1, \qquad \forall\, r \in R,\ d \in D \tag{A.5.8}$$

$$\theta_{rdvu} \leq \sum_{i\in K\cup R:\ i\neq r} x_{irvu},\ \forall\, r \in R,\ d \in D,\ v \in V^T,\ u \in \{1,\dots,U_v\} \tag{A.5.9}$$

$$\sum_{r\in R}\sum_{d\in D} \theta_{rdvu} w_d \leq z_v, \qquad \forall\, v \in V^T,\ u \in \{1,\dots,U_v\} \tag{A.5.10}$$

$$\sum_{v\in V^I}\sum_{u=1}^{U_v} \eta_{rdvu} = 1, \qquad \forall\, r \in R,\ d \in D \tag{A.5.11}$$

$$\eta_{rdvu} \leq \sum_{i\in K\cup R:\ i\neq r} x_{irvu}, \quad \forall\, r \in R,\ d \in D,\ v \in V^I,\ u \in \{1,\dots,U_v\} \tag{A.5.12}$$

$$\eta_{rdvu} \leq \rho_{rvu}, \qquad \forall\, r \in R,\ d \in D,\ v \in V^I,\ u \in \{1,\dots,U_v\} \tag{A.5.13}$$

$$e_{v(u-1)} + \sum_{r\in R}\sum_{d\in D} t^L_d \theta_{rdvu} \le q_{vu}, \ \forall\ v \in V^T,\ u \in \{1,...,U_v\} \tag{A.5.14}$$

$$e_{v(u-1)} \le q_{vu}, \ \forall\ v \in V\backslash V^T,\ u \in \{1,...,U_v\} \tag{A.5.15}$$

$$q_{vu} + t^T_{krv} - P(1 - x_{krvu}) \le s_{rvu}, \ \forall\ k \in K,\ r \in R,\ v \in V,\ u \in \{1,...,U_v\} \tag{A.5.16}$$

$$s_{rvu} - P(1 - \theta_{rdvu}) \le f_{rd}, \ \forall\ r \in R,\ d \in D,\ v \in V^T,\ u \in \{1,...,U_v\} \tag{A.5.17}$$

$$s_{rvu} + t^{PJ}_v - P(1 - \eta_{rdvu}) \le f_{rd}, \ \forall\ r \in R,\ d \in D,\ v \in V^I,\ u \in \{1,...,U_v\} \tag{A.5.18}$$

$$f_{rd_{m-1}} + \sum_{v\in V^I}\sum_{u=1}^{U_v} \eta_{rd_{m-1}vu} t^I_{d_{m-1}v} \le f_{rd_m}, \qquad \forall\ r \in R,\ m \in 2,...,|D| \tag{A.5.19}$$

$$f_{rd} + t^A_{dv} - P(1 - \theta_{rdvu}) \le h_{rvu}, \ \forall\ r \in R,\ d \in D,\ v \in V^T,\ u \in \{1,...,U_v\} \tag{A.5.20}$$

$$f_{rd} + t^I_{dv} - P(1 - \eta_{rdvu}) \le g_{rvu}, \ \forall\ r \in R,\ d \in D,\ v \in V^I,\ u \in \{1,...,U_v\} \tag{A.5.21}$$

$$g_{rvu} + t^{PJ}_v - P(1 - \rho_{rvu}) \le h_{rvu}, \ \forall\ r \in R,\ v \in V^I,\ u \in \{1,...,U_v\} \tag{A.5.22}$$

$$h_{ivu} + t^T_{ijv} - P(1 - x_{ijvu}) \le s_{jvu}, \ \forall\ i \in R,\ j \in R\ (i \neq j),\ v \in V,\ u \in \{1,...,U_v\} \tag{A.5.23}$$

$$h_{rvu} + t^T_{rkv} - P(1 - x_{rkvu}) \le e_{vu}, \ \forall\ k \in K,\ r \in R,\ v \in V,\ u \in \{1,...,U_v\} \tag{A.5.24}$$

$$s_{rvu} \le h_{rvu}, \ \forall\ r \in R,\ v \in V,\ u \in \{1,...,U_v\} \tag{A.5.25}$$

$$e_{vu} \le P, \quad \forall\ v \in V,\ u \in \{0,...,U_v\} \tag{A.5.26}$$

$$e_{vu} - e_{v0} \le E_v, \quad \forall\ v \in V,\ u \in \{1,...,U_v\} \tag{A.5.27}$$

A.6 WEATHER WINDOW PARAMETERS

W^T_v: Number of weather windows for transiting with vessel $v \in V$
W^{PJ}_v: Number of weather windows for positioning vessel $v \in V^I \subseteq V$
W^I_{dv}: Number of weather windows for installing components of type $d \in D$ with vessel $v \in V^I \subseteq V$
a^T_{vn}: Start of weather window $n \in \{1,..., W^T_v\}$ for transit with vessel $v \in V$
b^T_{vn}: End of weather window $n \in \{1,..., W^T_v\}$ for transit with vessel $v \in V$
a^{PJ}_{vn}: Start of weather window $n \in \{1,..., W^{PJ}_v\}$ for setup with vessel $v \in V^I \subseteq V$
b^{PJ}_{vn}: End of weather window $n \in \{1,..., W^{PJ}_v\}$ for setup with vessel $v \in V^I \subseteq V$
a^I_{dvn}: Start of weather window $n \in \{1,..., W^I_d\}$ for installing components of type $d \in D$ with vessel $v \in V^I \subseteq V$
b^I_{dvn}: End of weather window $n \in \{1,..., W^I_d\}$ for installing components of type $d \in D$ with vessel $v \in V^I \subseteq V$

A.7 WEATHER WINDOW VARIABLES

$$N^T_{ijvun} = \begin{cases} 1, & \text{if vessel } v \in V \text{ transits from location } i \in K \cup R \text{ to } j \in K \cup R \ (i \neq j) \\ & \text{on cycle } u \in \{1, \ldots, U_v\} \text{ in weather window } n \in \{1, \ldots, W^T_v\}, \\ 0, & \text{otherwise} \end{cases}$$

$$N^{PJ1}_{rvun} = \begin{cases} 1, & \text{if vessel } v \in V^I \subseteq V \text{ enters installation position at turbine } r \in R \\ & \text{on cycle } u \in \{1, \ldots, U_v\} \text{ in weather window } n \in \{1, \ldots, W^{PJ}_v\}, \\ 0, & \text{otherwise} \end{cases}$$

$$N^{PJ2}_{rvun} = \begin{cases} 1, & \text{if vessel } v \in V^I \subseteq V \text{ exits installation position at turbine } r \in R \\ & \text{on cycle } u \in \{1, \ldots, U_v\} \text{ in weather window } n \in \{1, \ldots, W^{PJ}_v\}, \\ 0, & \text{otherwise} \end{cases}$$

$$N^I_{rdvn} = \begin{cases} 1, & \text{if component type } d \in D \text{ at turbine location } r \in R \\ & \text{is installed by vessel } v \in V^I \subseteq V \text{ in weather} \\ & \text{window } n \in \{1, \ldots, W^I_{dv}\}, \\ 0, & \text{otherwise} \end{cases}$$

A.8 WEATHER WINDOW CONSTRAINTS

A.8.1 *Transit*

$$\sum_{k \in K} \sum_{r \in R} \sum_{n=1}^{W^T_v} N^T_{krvun} a^T_{vn} \leq q_{vu}, \ \forall \ v \in V, \ u \in \{1, \ldots, U_v\} \tag{A.8.1}$$

$$q_{vu} + \sum_{k \in K} \sum_{r \in R} x_{krvu} t^T_{krv} \leq \sum_{k \in K} \sum_{r \in R} \sum_{n=1}^{W^T_v} N^T_{krvun} b^T_{vn}, \ \forall \ v \in V, \ u \in \{1, \ldots, U_v\} \tag{A.8.2}$$

$$\sum_{n=1}^{W^T_v} N^T_{ijvun} a^T_{vn} \leq h_{ivu}, \ \forall \ i \in R, \ j \in K \cup R \ (i \neq j), \ v \in V, \ u \in \{1, \ldots, U_v\} \tag{A.8.3}$$

$$h_{ivu} + t^T_{ijv} - P(1 - x_{ijvu}) \leq \sum_{n=1}^{W^T_v} N^T_{ijvun} b^T_{vn}, \ \forall \ i \in R, \ j \in K \cup R \ (i \neq j), \ v \in V, \ u \in \{1, \ldots, U_v\} \tag{A.8.4}$$

$$\sum_{n=1}^{W^T_v} N^T_{ijvun} = x_{ijvu}, \ \forall \ i \in K \cup R, \ j \in K \cup R \ (i \neq j), \ v \in V, \ u \in \{1, \ldots, U_v\} \tag{A.8.5}$$

A.8.2 *Jack-up*

$$\sum_{n=1}^{W_v^{PJ}} N_{rvun}^{PJ1} a_{vn}^{PJ} \leq s_{rvu}, \quad \forall\ r \in R,\ v \in V^I,\ u \in \{1,\ldots,U_v\} \tag{A.8.6}$$

$$s_{rvu} + t_v^{PJ} - P(1-\rho_{rvu}) \leq \sum_{n=1}^{W_v^{PJ}} N_{rvun}^{PJ1} b_{vn}^{PJ}, \quad \forall\ r \in R,\ v \in V^I,\ u \in \{1,\ldots,U_v\} \tag{A.8.7}$$

$$\sum_{n=1}^{W_v^{PJ}} N_{rvun}^{PJ1} = \rho_{rvu}, \quad \forall\ r \in R,\ v \in V^I,\ u \in \{1,\ldots,U_v\} \tag{A.8.8}$$

A.8.3 *Installation*

$$\sum_{v \in V^I} \sum_{n=1}^{W_d^I} N_{rdvn}^I a_{dvn}^I \leq f_{rd}, \qquad \forall\ r \in R,\ d \in D \tag{A.8.9}$$

$$f_{rd} + \sum_{v \in V^I} \sum_{u=1}^{U_v} \eta_{rdvu} t_{dv}^I \leq \sum_{v \in V^I} \sum_{n=1}^{W_d^I} b_{dvn}^I N_{rdvn}^I, \qquad \forall\ r \in R,\ d \in D \tag{A.8.10}$$

$$\sum_{v \in V^I} \sum_{n=1}^{W_d^I} N_{rdvn}^I = 1, \quad \forall\ r \in R,\ d \in D \tag{A.8.11}$$

A.8.4 *Jack-down*

$$\sum_{n=1}^{W_v^{PJ}} N_{rvun}^{PJ2} a_{vn}^{PJ} \leq g_{rvu},\ \forall\ r \in R,\ v \in V^I,\ u \in \{1,\ldots,U_v\} \tag{A.8.12}$$

$$g_{rvu} + t_v^{PJ} - P(1-\rho_{rvu}) \leq \sum_{n=1}^{W_v^{PJ}} N_{rvun}^{PJ2} b_{vn}^{PJ},\ \forall\ r \in R,\ v \in V^I,\ u \in \{1,\ldots,U_v\} \tag{A.8.13}$$

$$\sum_{n=1}^{W_v^{PJ}} N_{rvun}^{PJ2} = \rho_{rvu}, \quad \forall\ r \in R,\ v \in V^I,\ u \in \{1,\ldots,U_v\} \tag{A.8.14}$$

B

MATHEMATICAL FORMULATION OF MODEL 2

B.1 SETS

K: Set of ports

V: Set of vessel strategies

B.2 PARAMETERS

c_k^K: Fixed cost operating from port $k \in K$

c_v^{TC}: Time charter cost per time unit for vessel strategy $v \in V$

c_v^M: Mobilization cost for starting chartering of vessel strategy $v \in V$

t_v^L: Time needed to load one turbine with vessel strategy $v \in V$

t_v^I: Time to install a turbine with vessel strategy $v \in V$

t_v^T: Time for turbine transits with vessel strategy $v \in V$

t_v^{PJ}: Time to enter/exit installation position with vessel strategy $v \in V$

t_{kv}^K: Time for port transits from port $k \in K$ with vessel strategy $v \in V$

Y_v: Maximum number of turbines installed per cycle with vessel strategy $v \in V$

U_v: Maximum number of cycles possible with vessel strategy $v \in V$

R: Total number of wind turbines

P: Length of time horizon

$S_v = P - t_v^I - t_v^{PJ} - \min_{k \in K}\{t_{kv}^K\}$

$F_v = P - t_v^{PJ} - \min_{k \in K}\{t_{kv}^K\}$

$H_v = P - \min_{k \in K}\{t_{kv}^K\}$

B.3 VARIABLES

$$\delta_k = \begin{cases} 1, & \text{if port } k \in K \text{ is in use,} \\ 0, & \text{otherwise} \end{cases}$$

$$\gamma_v = \begin{cases} 1, & \text{if vessel strategy } v \in V \text{ is used,} \\ 0, & \text{otherwise} \end{cases}$$

$$x_{kvu} = \begin{cases} 1, & \text{if vessel strategy } v \in V \text{ is run from port } k \in K \text{ on cycle } u \in \{1, ..., U_v\}, \\ 0, & \text{otherwise} \end{cases}$$

$$\theta_{vuy} = \begin{cases} 1, & \text{if vessel strategy } v \in V \text{ runs } u \in \{1, ..., U_v\} \text{ or more cycles installing} \\ & \text{turbine } y \in \{1, ..., Y_v\}, \\ 0, & \text{otherwise} \end{cases}$$

$q_{vu} \in \mathbb{R}_+$: Time when vessel strategy $v \in V$ starts cycle $u \in \{1, ..., U_v\}$

$e_{vu} \in \mathbb{R}_+$: Time when vessel strategy $v \in V$ ends cycle $u \in \{0, ..., U_v\}$

$s_{vuy} \in \mathbb{R}_+$: Time when vessel strategy $v \in V$ arrives at turbine $y \in \{1, ..., Y_v\}$ on cycle $u \in \{1, ..., U_v\}$

$f_{vuy} \in \mathbb{R}_+$: Time when vessel strategy $v \in V$ starts installation of turbine $y \in \{1, ..., Y_v\}$ on cycle $u \in \{1, ..., U_v\}$

$g_{vuy} \in \mathbb{R}_+$: Time when vessel strategy $v \in V$ finish operations at turbine $y \in \{1, ..., Y_v\}$ on cycle $u \in \{1, ..., U_v\}$

$h_{vuy} \in \mathbb{R}_+$: Time when vessel strategy $v \in V$ leaves turbine $y \in \{1, ..., Y_v\}$ on cycle $u \in \{1, ..., U_v\}$

$E_v \in \mathbb{R}_+$: Total time vessel strategy $v \in V$ is chartered

B.4 OBJECTIVE FUNCTION

$$\min \sum_{k \in K} c_k^K \delta_k + \sum_{v \in V} \left(c_v^M \gamma_v + c_v^{TC} E_v \right)$$

B.5 CONSTRAINTS

$$\sum_{v\in V}\sum_{u=1}^{U_v}\sum_{y=1}^{Y_v}\theta_{vuy} \geq R, \tag{B.5.1}$$

$$\theta_{vuy} \leq \gamma_v, \quad \forall\ v\in V,\ u\in\{1,\dots,U_v\},\ y\in\{1,\dots,Y_v\} \tag{B.5.2}$$

$$x_{kvu} \leq \delta_k, \quad \forall\ k\in K,\ v\in V,\ u\in\{1,\dots,U_v\} \tag{B.5.3}$$

$$\sum_{k\in K} x_{kvu} \leq 1, \qquad \forall\ v\in V, u\in\{1,\dots,U_v\} \tag{B.5.4}$$

$$x_{kvu} \leq x_{kv(u-1)}, \quad \forall\ k\in K,\ v\in V,\ u\in\{2,\dots,U_v\} \tag{B.5.5}$$

$$\theta_{vu1} \leq \sum_{k\in K} x_{kvu},\ \forall\ v\in V,\ u\in\{1,\dots,U_v\} \tag{B.5.6}$$

$$\theta_{vuy} \leq \theta_{vu(y-1)},\ \forall\ v\in V,\ u\in\{1,\dots,U_v\},\ y\in\{2,\dots,Y_v\} \tag{B.5.7}$$

$$\sum_{y=1}^{Y_v}\theta_{vuy} \leq \sum_{y=1}^{Y_v}\theta_{v(u-1)y},\ \forall\ v\in V,\ u\in\{2,\dots,U_v\} \tag{B.5.8}$$

$$e_{v(u-1)} + \sum_{y=1}^{Y_v} t_v^L\theta_{vuy} \leq q_{vu},\ \forall\ v\in V,\ u\in\{1,\dots,U_v\} \tag{B.5.9}$$

$$q_{vu} + \sum_{k\in K} t_{kv}^K x_{kvu} \leq s_{vu1},\ \forall\ v\in V,\ u\in\{1,\dots,U_v\} \tag{B.5.10}$$

$$s_{vuy} + t_v^{PJ} - S_v(1-\theta_{vuy}) \leq f_{vuy},\ \forall\ v\in V,\ u\in\{1,\dots,U_v\},\ y\in\{1,\dots,Y_v\} \tag{B.5.11}$$

$$f_{vuy} + t_v^{I} - F_v(1-\theta_{vuy}) \leq g_{vuy},\ \forall\ v\in V,\ u\in\{1,\dots,U_v\},\ y\in\{1,\dots,Y_v\} \tag{B.5.12}$$

$$g_{vuy} + t_v^{PJ} - H_v(1-\theta_{vuy}) \leq h_{vuy},\ \forall\ v\in V,\ u\in\{1,\dots,U_v\},\ y\in\{1,\dots,Y_v\} \tag{B.5.13}$$

$$h_{vu(y-1)} + t_v^{T} - H_v(1-\theta_{vuy}) \leq s_{vuy},\ \forall\ v\in V,\ u\in\{1,\dots,U_v\},\ y\in\{2,\dots,Y_v\} \tag{B.5.14}$$

$$h_{vuy} + \sum_{k\in K} t_{kv}^T x_{kvu} \leq e_{vu},\ \forall\ v\in V,\ u\in\{1,\dots,U_v\},\ y\in\{1,\dots,Y_v\} \tag{B.5.15}$$

$$e_{vu} \leq P, \quad \forall\ v\in V,\ u\in\{0,\dots,U_v\} \tag{B.5.16}$$

$$e_{vu} - e_{v0} \leq E_v, \quad \forall\ v\in V,\ u\in\{1,\dots,U_v\} \tag{B.5.17}$$

B.6 WEATHER WINDOW PARAMETERS

W_v^I: Number of weather windows for installing a turbine with strategy $v \in V$
W_v^{PJ}: Number of weather windows for positioning with strategy $v \in V$
W_v^T: Number of weather windows for transiting with strategy $v \in V$
a_{vn}^I: Start of weather window $n \in \{1,...,W_d^I\}$ for installing with strategy $v \in V$
b_{vn}^I: End of weather window $n \in \{1,...,W_d^I\}$ for installing with strategy $v \in V$
a_{vn}^{PJ}: Start of weather window $n \in \{1,...,W_v^{PJ}\}$ for positioning with strategy $v \in V$
b_{vn}^{PJ}: End of weather window $n \in \{1,...,W_v^{PJ}\}$ for positioning with strategy $v \in V$
a_{vn}^T: Start of weather window $n \in \{1,...,W_v^T\}$ for transiting with strategy $v \in V$
b_{vn}^T: End of weather window $n \in \{1,...,W_v^T\}$ for transiting with strategy $v \in V$

B.7 WEATHER WINDOW VARIABLES

$$N_{vuyn}^I = \begin{cases} 1, & \text{if turbine } y \in \{1,..,Y_v\} \text{ on cycle } u \in \{1,...,U_v\} \text{ is installed with strategy } v \in V \\ & \text{in weather window } n \in \{1,...,W_v^I\}, \\ 0, & \text{otherwise} \end{cases}$$

$$N_{vuyn}^{PJ1} = \begin{cases} 1, & \text{if strategy } v \in V \text{ enters position at turbine } y \in \{1,..,Y_v\} \text{ on cycle } u \in \{1,...,U_v\} \\ & \text{in weather window } n \in \{1,...,W_v^{PJ}\}, \\ 0, & \text{otherwise} \end{cases}$$

$$N_{vuyn}^{PJ2} = \begin{cases} 1, & \text{if strategy } v \in V \text{ exits position at turbine } y \in \{1,..,Y_v\} \text{ on cycle } u \in \{1,...,U_v\} \\ & \text{in weather window } n \in \{1,...,W_v^{PJ}\}, \\ 0, & \text{otherwise} \end{cases}$$

$$N_{vuyn}^T = \begin{cases} 1, & \text{if strategy } v \in V \text{ transits to turbine } y \in \{1,..,Y_v+1\} \text{ on cycle } u \in \{1,...,U_v\} \\ & \text{in weather window } n \in \{1,...,W_v^T\}, \\ 0, & \text{otherwise} \end{cases}$$

B.8 WEATHER WINDOW CONSTRAINTS

B.8.1 *Transit*

$$\sum_{n=1}^{W_v^T} N_{vu1n}^T a_{vn}^T \le q_{vu}, \qquad \forall\ v \in V,\ u \in \{1,\dots,U_v\} \tag{B.8.1}$$

$$q_{vu} + \sum_{k\in K} t_{kv}^K x_{kvu} - S_v(1-\theta_{vu1}) \le \sum_{n=1}^{W_v^T} N_{vu1n}^T b_{vn}^T, \qquad \forall\ v \in V,\ u \in \{1,\dots,U_v\} \tag{B.8.2}$$

$$\sum_{n=1}^{W_v^T} N_{vu(y+1)n}^T a_{vn}^T \le h_{vuy}, \qquad \forall\ v \in V,\ u \in \{1,\dots,U_v\} \quad y \in \{1,\dots,Y_v\} \tag{B.8.3}$$

$$h_{vu(y-1)} + t_v^T - H_v(1-\theta_{vuy}) \le \sum_{n=1}^{W_v^T} N_{vuyn}^T b_{vn}^T, \qquad \forall\ v \in V,\ u \in \{1,\dots,U_v\}, \quad y \in \{2,\dots,Y_v\} \tag{B.8.4}$$

$$h_{vuy} + \sum_{k\in K} t_{kv}^K x_{kvu} - H_v(1-\theta_{vuy} + \theta_{vu(y+1)}) \le \sum_{n=1}^{W_v^T} N_{vu(y+1)n}^T b_{vn}^T, \qquad \forall\ v \in V,\ u \in \{1,\dots,U_v\}, \quad y \in \{1,\dots,Y_v - 1\} \tag{B.8.5}$$

$$h_{vuY_v} + \sum_{k\in K} t_{kv}^K x_{kvu} - H_v(1-\theta_{vuY_v}) \le \sum_{n=1}^{W_v^T} N_{vu(Y_v+1)n}^T b_{vn}^T, \qquad \forall\ v \in V,\ u \in \{1,\dots,U_v\} \tag{B.8.6}$$

$$\sum_{n=1}^{W_v^T} N_{vu1n}^T = \theta_{vu1}, \qquad \forall\ v \in V,\ u \in \{1,\dots,U_v\} \tag{B.8.7}$$

$$\sum_{n=1}^{W_v^T} N_{vu(y+1)n}^T = \theta_{vuy}, \qquad \forall\ v \in V,\ u \in \{1,\dots,U_v\}, \quad y \in \{1,\dots,Y_v\} \tag{B.8.8}$$

B.8.2 *Jack-up*

$$\sum_{n=1}^{W_v^{PJ}} N_{vuyn}^{PJ1} a_{vn}^{PJ} \leq s_{vuy}, \quad \forall\ v \in V,\ u \in \{1,\dots,U_v\},\ y \in \{1,\dots,Y_v\} \tag{B.8.9}$$

$$s_{vuy} + t_v^{PJ} - S_v(1-\theta_{vuy}) \leq \sum_{n=1}^{W_v^{PJ}} N_{vuyn}^{PJ1} b_{vn}^{PJ}, \quad \forall\ v \in V,\ u \in \{1,\dots,U_v\},\ y \in \{1,\dots,Y_v\} \tag{B.8.10}$$

$$\sum_{n=1}^{W_v^{PJ}} N_{vuyn}^{PJ1} = \theta_{vuy}, \quad \forall\ v \in V,\ u \in \{1,\dots,U_v\},\ y \in \{1,\dots,Y_v\} \tag{B.8.11}$$

B.8.3 *Installation*

$$\sum_{n=1}^{W_v^{PJ}} N_{vuyn}^{I} a_{vn}^{PJ} \leq f_{vuy}, \quad \forall\ v \in V,\ u \in \{1,\dots,U_v\},\ y \in \{1,\dots,Y_v\} \tag{B.8.12}$$

$$f_{vuy} + t_v^{I} - F_v(1-\theta_{vuy}) \leq \sum_{n=1}^{W_v^{PJ}} N_{vuyn}^{I} b_{vn}^{PJ}, \quad \forall\ v \in V,\ u \in \{1,\dots,U_v\},\ y \in \{1,\dots,Y_v\} \tag{B.8.13}$$

$$\sum_{n=1}^{W_v^{PJ}} N_{vuyn}^{I} = \theta_{vuy}, \quad \forall\ v \in V,\ u \in \{1,\dots,U_v\},\ y \in \{1,\dots,Y_v\} \tag{B.8.14}$$

B.8.4 *Jack-down*

$$\sum_{n=1}^{W_v^{PJ}} N_{vuyn}^{PJ2} a_{vn}^{PJ} \leq g_{vuy}, \quad \forall\ v \in V,\ u \in \{1,\dots,U_v\},\ y \in \{1,\dots,Y_v\} \tag{B.8.15}$$

$$g_{vuy} + t_v^{PJ} H_v(1-\theta_{vuy}) \leq \sum_{n=1}^{W_v^{PJ}} N_{vuyn}^{PJ2} b_{vn}^{PJ}, \quad \forall\ v \in V,\ u \in \{1,\dots,U_v\},\ y \in \{1,\dots,Y_v\} \tag{B.8.16}$$

$$\sum_{n=1}^{W_v^{PJ}} N_{vuyn}^{PJ2} = \theta_{vuy}, \quad \forall\ v \in V,\ u \in \{1,\dots,U_v\},\ y \in \{1,\dots,Y_v\} \tag{B.8.17}$$

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